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Washington, D.C. 20591

# System Safety Study of Minimum TCAS II

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The MITRE Corporation
McLean, Virginia 22102

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December 1983

Final Report

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16. Abstract

A System Safety study was conducted to assess the overall safety characteristics associated with use of the airborne collision avoidance system called minimum TCAS II (Traffic Alert and Collision Avoidance System). The limitations imposed by incomplete transponder equipage, altimetry instrumentation errors, and suddenly maneuvering intruders were quantified. Other failure mechanisms, including those related to human factors, were also assessed. The role of visual acquisition and a quantitative evaluation of it was explored. The impact on System Safety caused by the failure modes and their interrelations was evaluated by means of a fault tree analysis.

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# METRIC CONVERSION FACTORS

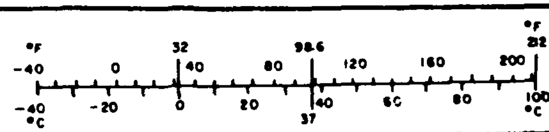
### Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.


### Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |




60 mph = 52.1 knots (nautical miles per hour)

60 mph = 88'/sec $\quad$ 1g = 32.2'$sec^2$

1 mph = .87 knots

1 knot - 1.15 mph

# FOREWORD

The TCAS System Safety study was initiated within the TCAS Program of the Federal Aviation Administration (FAA) shortly after the Third TCAS Symposium as a means for formalizing several ongoing analyses of TCAS performance and to address specific safety concerns voiced by the aviation community. Five reviews of study progress were held at FAA Headquarters during the 10-month study period in which a broad spectrum of the aviation community participated. This participation was very helpful in providing feedback to the study team from the prospective user community and also to assure that all major topics of interest were considered.

The study team, headed by the MITRE Corporation, developed a comprehensive methodology for the analyses of TCAS safety in addition to providing a quantitative evaluation of TCAS performance. The sensitivity analysis conducted as part of the overall study is of particular importance since this analysis clearly delineates the effect of system parameter modification upon system safety. Specifically, it is shown that increasing the TCAS logic parameter, ALIM, by less than 20 percent at the lower altitude bands reduced the effects of altimetry error by approximately 50 percent. On the basis of this analysis, the ALIM values specified for the TCAS Minimum Operational Performance Standards (MOPS) were modified accordingly.

In the near future a new study will be conducted to extend the safety study results for air carrier flight in Instrument Meteorological Conditions (IMC). This study will assess the safety of TCAS usage in controlled airspace in which virtually all participants are operating under Instrument Flight Rules (IFR), and will consider the effects of relative geometry and dynamics, operational factors and other pertinent parameters affecting the utilization of TCAS in this flight regime.

Joe Fee, Director
TCAS System Safety Study
11/10/83

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## ACKNOWLEDGEMENT

The participation, critical questioning, and insightful comments of many people contributed to the results of this study. The government and industry reviewers, whose names are listed in Appendix A, were very effective; their views were always helpful and considered.

This report was produced and edited by the MITRE Corporation, with substantial contributions by the organizations participating in the TCAS System Safety study. Authorship was comprised of technical staff from these organizations. Development, analysis and evaluation of the fault trees was performed by J. E. Lebron; maneuvering intruder and hardware failures, by A. D. Zeitlin; and the study of near midair collisions and effects of altimetry error, by N. A. Spencer -- all the MITRE Corporation. The study and evaluation of visual acquisition was performed by J. W. Andrews of M.I.T. Lincoln Laboratory; and the analysis of TCAS Surveillance Characteristics, by Dr. W. H. Harman, also of Lincoln Laboratory. At the FAA Technical Center, B. R. Billmann and A. L. Adkins provided the analysis of FAA flight data, of Mode C bit-error characteristics, and of TCAS logic performance. Finally, T. A. Morgan at FAA Headquarters did the research and analysis of errors in Mode C altitude reports.

In addition to the authors, contributions to the text were made by Michael Lenard and Stephen Mulder, both of MITRE. Joseph Fee, FAA Headquarters, provided helpful critique of the analyses, as well as contributing to the analyses in a key manner.

The entire project owes a large debt of gratitude for secretarial services to Diane Brown and Nadia Kalagher of the MITRE Corporation, who suffered through many deadlines and revisions in a very short time.

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## EXECUTIVE SUMMARY

### 1. Introduction

This report describes a System Safety study, which was conducted to assess the overall safety characteristics associated with use of the Minimum TCAS II airborne collision avoidance system. Emphasis has been placed on principal limitations and failure mechanisms. The System Safety study, an overall assessment of the interrelation of avionics, the pilots, and the air traffic advisory system, uses the "fault tree" technique to structure a "top down" analytical approach.

The TCAS system is a cooperative one in that information on the intruder is obtained by interrogating its ATC transponder and then predicting whether the aircraft will approach too closely within the next half-minute. The system must consider the following basic limitations:

- Lack of universal Mode C equipage
- Errors in reported altimetry
- Susceptibility to being deceived by an intruder's sudden maneuver

In addition, the internal failure mechanisms treated are as follows:

- The surveillance function of TCAS
- Bit errors in the intruder's transponder reply of altitude
- Avionics failures

A related mode of failure includes pilot errors in using a normally performing TCAS. All of these events are evaluated in this System Safety study.

For the purpose of the study, these limitations and failure mechanisms are those faults which could result in a near midair collision (NMAC). An NMAC is defined here as an encounter for which, at the closest point of approach, the vertical separation is less than 100 ft and the horizontal separation is less than 500 ft.

In a TCAS II environment NMACs can occur in either of two ways: the aircraft can be on near collision course and TCAS II fails to provide resolution (the unresolved NMAC); or the aircraft can be in close proximity and TCAS II can induce a maneuver which degrades vertical separation to the extent that an NMAC occurs (the induced NMAC).

To evaluate the relative effect of TCAS on System Safety, a term called "Risk Ratio" is defined and computed using real-world data. This factor is the risk of encountering an NMAC when equipped with TCAS, relative to the risk when not so equipped. Using the NMAC as a defined failure condition provides a quantitative measure for calculations; using the Risk Ratio places the calculations of System Safety on a direct comparative basis. A framework for combining these probabilities is provided by a formal fault tree analysis of the events which, in combination, could lead to an NMAC.

Succeeding sections deal with the conduct of the study itself. The results are summarized in Section 9 and the conclusions are given in Section 10.

## 2. Overview of Minimum TCAS II

The minimum TCAS II uses active interrogation of ATC transponders to track nearby aircraft in slant range and relative altitude; it uses these to assess the collision threat potential and to generate appropriate collision avoidance advisories. It provides the pilot with Traffic Advisories (TAs) and with Resolution Advisories (RAs). In collision encounters, the system design assures that the TA normally occurs approximately 15 seconds before the RA. The TA can be presented, perhaps on a weather radar CRT display, in a graphical format which provides the range, bearing, and relative altitude of the potential threat.

As an option, non-Mode C aircraft may also be tracked. If an intruding aircraft is not reporting altitude through its transponder, it is not possible to determine if the aircraft is a potential collision threat. Therefore, for intruders not equipped with altitude reporting, TCAS II may generate TAs but will not generate RAs. However, if the aircraft were on near collision course, such TAs would enhance visual acquisition.

An aircraft is declared to be a collision threat to the TCAS aircraft if its current position, or its projected position, simultaneously violate range and relative altitude criteria. Generally, an aircraft will be declared to be a collision threat 20-30 seconds before closest approach, at which time an RA is displayed. This provides time for an escape maneuver by the pilot.

The RA (e.g., Climb, Descend, Don't Climb, etc.) is chosen to provide a specific margin of separation with a minimum change in the existing flight path of the TCAS II aircraft. The minimum TCAS II utilizes maneuvers in the vertical plane only.

### 3. TCAS Environment

To characterize the environment of the average air carrier with TCAS, the following sources of data are used:

- Incident reports on NMACs collected by the FAA
- TCAS data as recorded on Piedmont Airlines operational flights
- TCAS operations as recorded on the FAA B727 aircraft in flights at Atlantic City, Washington, and Chicago.

Each of these data sources are examined, and cross checked, to obtain some measure of the probability of various events in the fault tree. The major findings from this investigation are the following:

- Bright daylight conditions occurred for 70 percent of the NMAC incidents. Visual acquisition will be conservatively assumed to be impossible for all other conditions.
- Instrument Meteorological Conditions (IMC) occurred for less than 16 percent of the NMAC incidents.
- The other aircraft in an NMAC incident report is equipped with a transponder in 92 percent of the cases. Of these, 66 percent are also equipped with Mode C (i.e., 61 percent of the threats have Mode C altitude reporting transponders).

- The distribution of conflicting aircraft in relative altitude at the closest point of approach is approximately uniform over a wide range of relative altitudes. This important result is used in the analyses. It was observed in the Piedmont flights, both for the RAs, and for the TAs; it was observed for all tracks recorded on flights with the FAA aircraft in the vicinity of Chicago, as well as Washington.

- Data was obtained for the distribution of altitude rates and the probability of a level-off maneuver. These enable a calculation of the susceptibility of TCAS being deceived by a sudden maneuver of a threat aircraft.

- The current risk of encountering an NMAC is estimated as 1 in 100,000 hours. This value is recognized as being approximate; it is roughly sustained by four different estimates. The principal analysis, however, is independent of this value, a relative comparison is obtained instead.

## 4. Principal Limitations

As a step in determining the probabilities of various events in the fault tree, estimates are made independently of the relative probability (Risk Ratio) of (1) the intruder being Mode C equipped, (2) of having excessive altimetry error, and (3) of making a sudden contrary maneuver.

### Mode C Equipage

Since it was found that about 61 percent of the intruders involved in an NMAC were equipped for Mode C altitude reporting, that represents the maximum benefit that the TCAS RA could provide in today's environment. That is, at best, 61 percent of the current NMACs could be avoided with today's level of equipage. However, a large fraction of aircraft involved in NMACs have transponders (92 percent), even if they do not have Mode C. If the non-Mode C tracking feature were available in TCAS, "altitude unknown" TAs could be provided. If the intruder is really on a near collision course, this feature, patterned after the ATC practice of announcing traffic of concern, should be helpful in alerting the TCAS pilot.

Altimetry Errors

The vertical separation between two conflicting aircraft is measured as the difference between own altitude and that of the intruder's altitude as reported in his Mode C reply. The TCAS aircraft is required to have relatively high accuracy altimetry, as is commonly found on air carrier aircraft; an intruding general aviation aircraft might have lower accuracy. The magnitudes of these errors are assessed and used in the calculations.

Errors in altimetry can cause two types of effects: first, if the aircraft are on a near collision course, errors could indicate safe passage, and so the impending NMAC would be unresolved; second, if the aircraft were almost on a near collision course, but were separated in altitude, errors could lead to making a maneuver which would lead to inducing an NMAC. These two effects are evaluated relative to the risk of encountering the NMAC without TCAS. Only some combinations of altimetry error and actual physical position can lead to these failures. The collision avoidance logic has various parameters designed to tolerate some degree of altimetry error, the principal parameter being ALIM, the nominal separation that TCAS tries to ensure. If the error is significantly less than

ALIM, the TCAS aircraft will maneuver through the error and be clear. If the error is nearly ALIM or more, the choice of maneuver can be wrong.

The Risk Ratio is calculated by identifying those combinations of altimetry error and geometrical position that could lead to an NMAC, and then weighting those combinations by their probabilities of occurrence. Geometrical position, as noted earlier, was found to be uniformly distributed; altimetry error is assumed normally (Gaussian) distributed. The result is then normalized to the probability of a pre-existing NMAC to obtain the Risk Ratio.

During the course of the study, it appeared desirable and convenient to obtain a substantial improvement by a modest change to the parameter ALIM at low altitudes. Making this change and assuming all intruders to have general aviation quality altimetry (uncorrected for static source error), the Risk Ratio, weighted to account for altitude distribution is 3.1 percent, as shown in Table 1. The meaning of this is that, if all aircraft in near encounters had that altimetry error characteristic, and any resulting Resolution Advisory were followed, the resulting number of NMACs would be 3.1 percent of those that would otherwise have occurred without TCAS. Of course, other factors enter into the complete picture -- not all intruders are mode C equipped; some have better altimetry; visual acquisition is improved by the Traffic Advisory display. The full picture is put together in Section 9, Findings.

The sensitivity to the assumed Gaussian distribution is also investigated by replacing it by a symmetrical exponential distribution having the same standard deviation, which has much

TABLE 1
EFFECTS OF ALTIMETRY ERROR FOR MODIFIED ALIM

| ALT. | ALIM | RSS ERROR (SIGMA) | FRACTION OF NMAC IN ALTITUDE BAND | RISK RATIO | WEIGHTED RISK RATIO |
|---|---|---|---|---|---|
| 5 Kft | 400 ft | 143 ft | .44 | .0269 | .0118 |
| 10 | 400 | 156 | .31 | .0485 | .0150 |
| 15 | 500 | 175 | .17 | .0231 | .0039 |
| 20 | 640 | 190 | .03 | .0051 | .0002 |
| 25 | 640 | 206 | .01 | .0117 | .0001 |
| 30 | 640 | 220 | .03 | .0210 | .0006 |
| 35 | 740 | 239 | .01 | .0125 | .0001 |

Total = .0317
Unresolved = .0143
Induced = .0174

Notes: Errors are 1. Own altimetry (A/C Quality)
2. Intruder altimetry (GA Quality)
3. 150 fpm tracking bias error

DELTA = 75 ft (Corrective advisory is maintained until the apparent separation is ALIM + 75 ft)

"heavier tails." The result of that investigation is found to be equivalent to that for a Gaussian distribution with a 15 percent higher error.

Maneuvering Intruder

If an intruder is equipped only with a transponder and Mode C encoder, but not with TCAS, there is no way to coordinate maneuvers. Thus, an escape maneuver on the part of the TCAS aircraft could be thwarted ("faked out") by a sudden contrary maneuver on the part of the intruder. In such a situation TCAS could be said to induce an NMAC. This characteristic is evaluated by accounting for the behavior of the collision avoidance logic and by using recorded data to characterize the intruder's maneuver. The scenario of most concern is one in which the TCAS aircraft is level, and the intruder has a substantial vertical rate and will cross in front of the TCAS aircraft. As an example, the TCAS aircraft is level and the intruder is descending to cross in front of TCAS. At the closest point of approach the intruder would be close horizontally and within ALIM below. TCAS will then display a Climb indication, which the pilot would presumably follow. In order for an NMAC to occur, the intruder must level off in a critical time window and at a critical altitude. Using data from the Piedmont flights, the probability of a maneuver within the time window, together with the observed vertical rates, were used to assess the susceptibility of TCAS to the fake-out. Relative to the pre-existing risk of an NMAC, the Risk Ratio is found to be 2.7 percent. Using the data from the FAA flights, instead of the Piedmont data, and using a different methodology for estimation, similar results are obtained.

## 5. Failure Mechanisms

The internal failure mechanisms pertain to (1) surveillance, (2) persistent bit errors in the intruder's reply of altitude, and (3) various combinations of failures in the avionics of either aircraft.

### Surveillance

Many hours of TCAS airborne data is examined, both from 1982 flights in a Boeing 727 and from 1983 flights in a Cessna 421. The analysis shows that, by far, the surveillance characteristic of most concern is the missed track rate. The typical performance is found to be a miss rate of .06 at the time of the TA, and .03 at the time of the RA.

### Mode C Bit Failure

The impact of a persistent Mode C encoder bit failure is examined. The failure of concern is a "stuck low order bit"; the high order bits are of much less concern, since they represent errors of 500 ft or more and are very likely to be detected by other means. The low order bits provide errors of 100 ft, and can go undetected; their principal potential harm is not in the altitude error itself but in the altitude rate, which can cause an erroneous 30-second prediction. The wrong combination of circumstances could cause an induced NMAC.

Data from TCAS flights, supplemented by data taken by ground radars at NASA's Wallops Island facility give a measure of the frequency of occurrence of this kind of failure. That is combined with the results of simulations on the TCAS altitude tracker to determine the ultimate effects. It is concluded that the Risk Ratio ascribable to a stuck C-bit is about 0.2 percent--considerably less than that arising from altimetry error or maneuvering intruders.

Equipment Failure

Some hardware failures in TCAS and in the intruder's transponder could cause an induced NMAC--a list of such generic failures is provided in Appendix F. To assure that this type of failure is remote, an approach is given which indicates a relation between mean time between failure, performance monitoring, and periodic maintenance to achieve these goals.

6. Visual Acqusition

The study assumes that if the pilot of the TCAS aircraft visually acquires a conflicting aircraft, he will avoid it. Data from flights made both on the TCAS program and on the earlier ground-based anticollision system, Intermittent Positive Control, validated a theoretical model of visual acquisition. Applying the results of the model to a variety of aircraft, crossing angles, and speeds, in clear weather, it is found that the probability of visual acquisition is about 0.83. In good weather, visual acqusition, as aided by the TCAS TAs, can play an important role in collision avoidance.

7. Fault Tree for TCAS Safety Analysis

The fault tree constructed for this study provides both a qualitative and a quantitative means to identify and analyze failure modes in the overall system. A fault tree identifies all possible means by which the undesired event (NMAC) can occur, organizes them into a logical structure to study the processes leading to failures, and systematically identifies all their root causes and interactions.

The two primary types of TCAS failures, which we are interested in evaluating are:

1. Two aircraft are on flight paths such that the pilot will need to make a maneuver in order to avoid an NMAC; TCAS does not provide an advisory adequate to enable the pilot to avoid it. This is an "Unresolved NMAC".

2. Two aircraft are on flight paths such that if no maneuver is made, an NMAC will not occur (the aircraft will pass safely in the vertical dimension). A faulty instruction is issued (in particular, a Resolution Advisory) which is followed, causing a critical NMAC to occur. This is an "Induced NMAC".

The top-level fault tree for these events is shown in Figure 1. Each of these events is further subdivided in the trees shown in Figures 2 and 3.

Table 2 is a summary of the basic probabilities obtained from the analyses conducted in this study. *From this data the failure rates* of various events in the fault tree can be obtained.

In addition to these quantified probabilities, there are human-factor considerations which are less easily quantified, there being no historical data base. These account for the use of visual acquisition, the use of the Traffic Advisory, and the use of the Resolution Advisory. In turn, these may be broken down further depending upon whether an action is taken or not taken.

- Visual Acquisition (V). Upon visual acquisition, as aided by TCAS, it is expected that the pilot will be able to avoid an NMAC. However, this might fail in one of two ways:

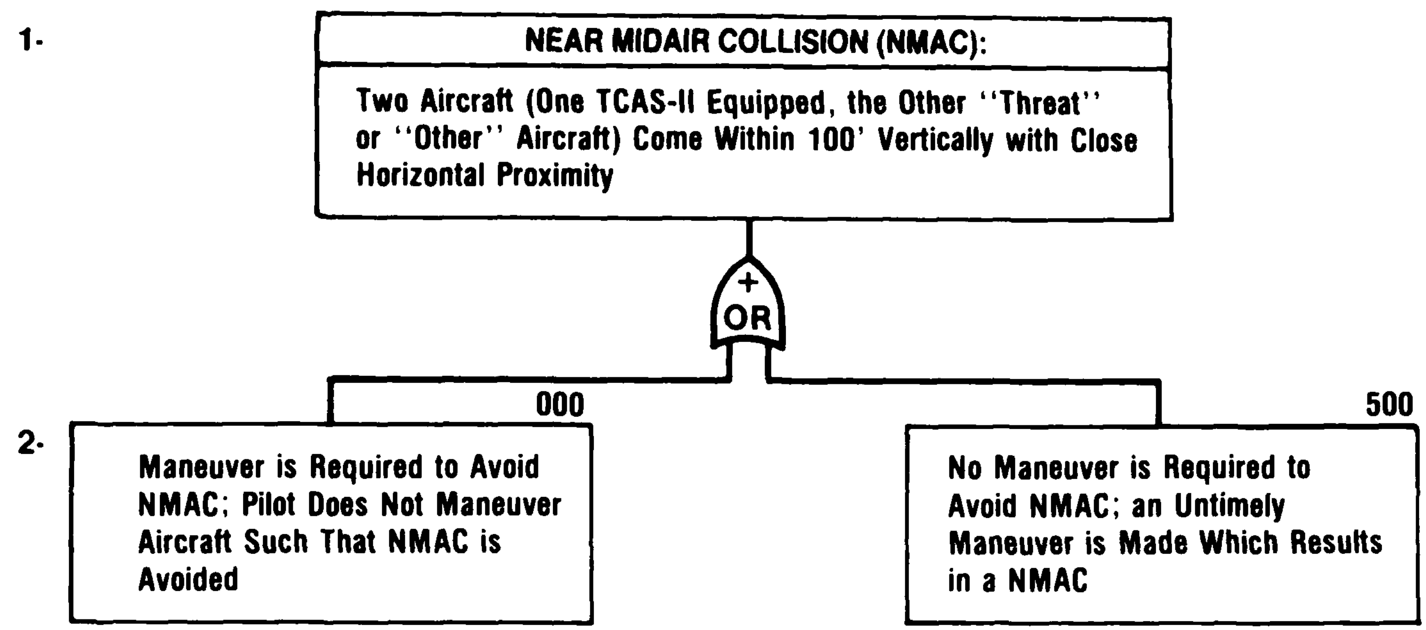
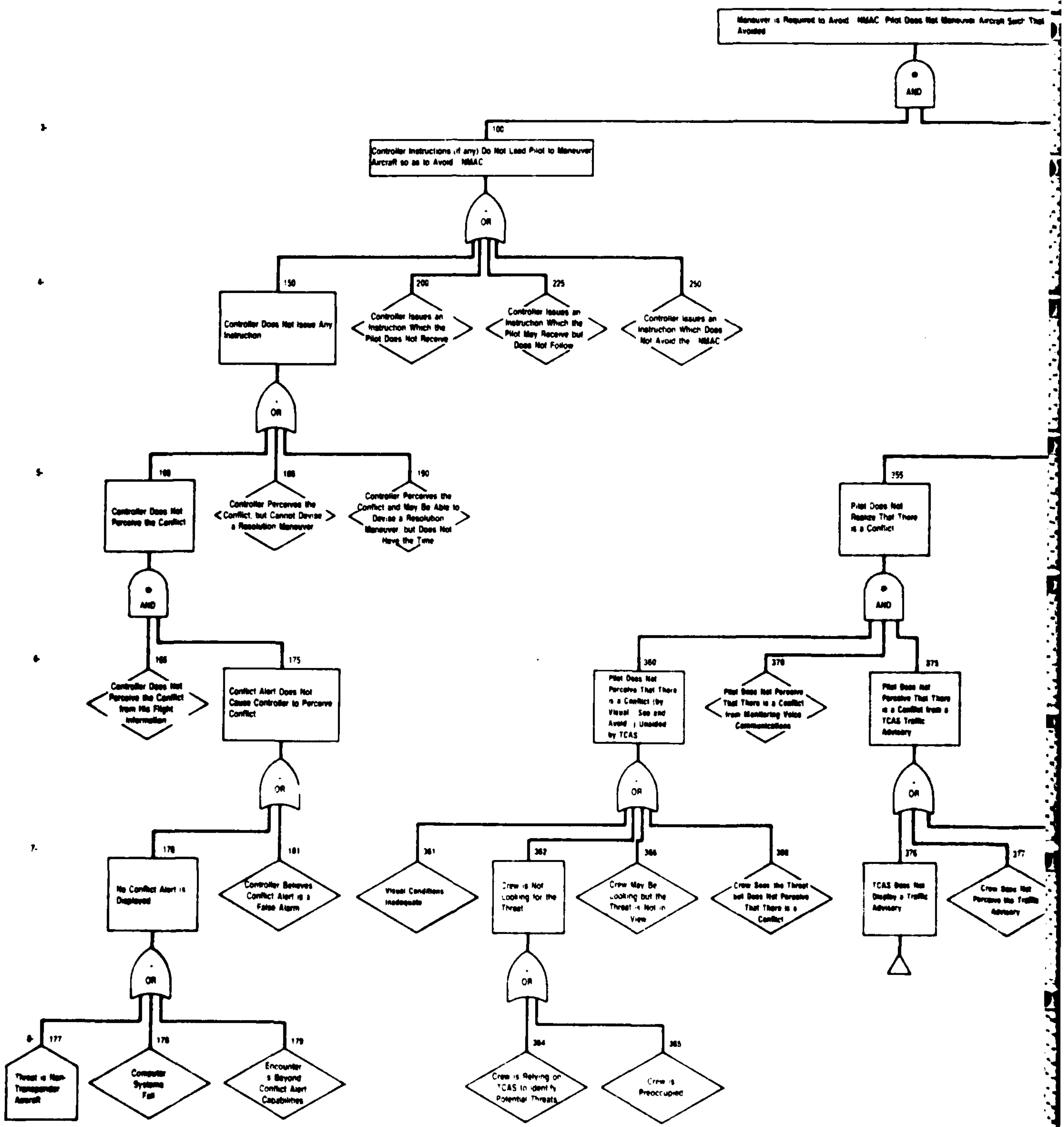



FIGURE 1
TCAS FAULT TREE: TOP EVENT (CRITICAL NMAC)



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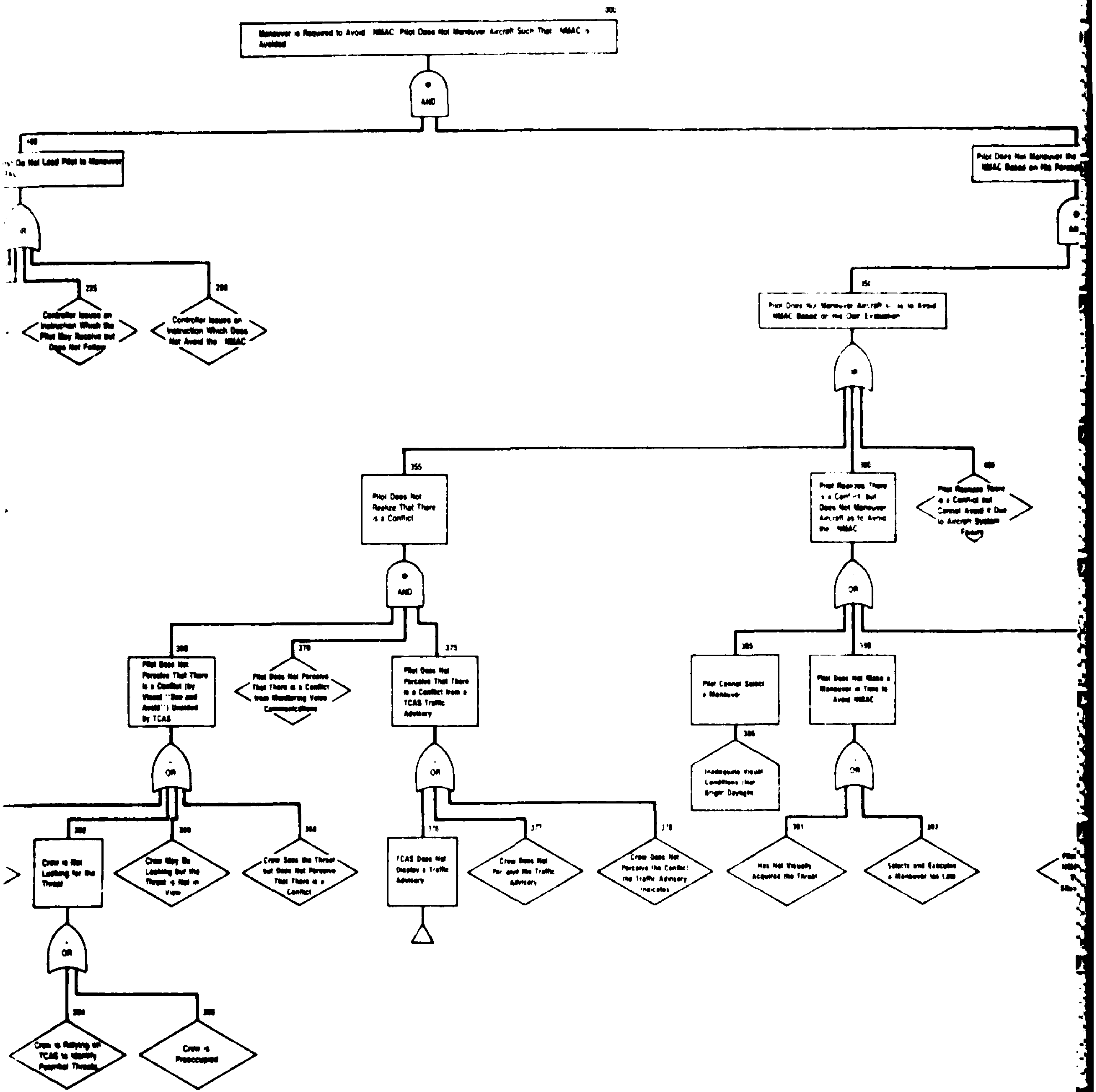


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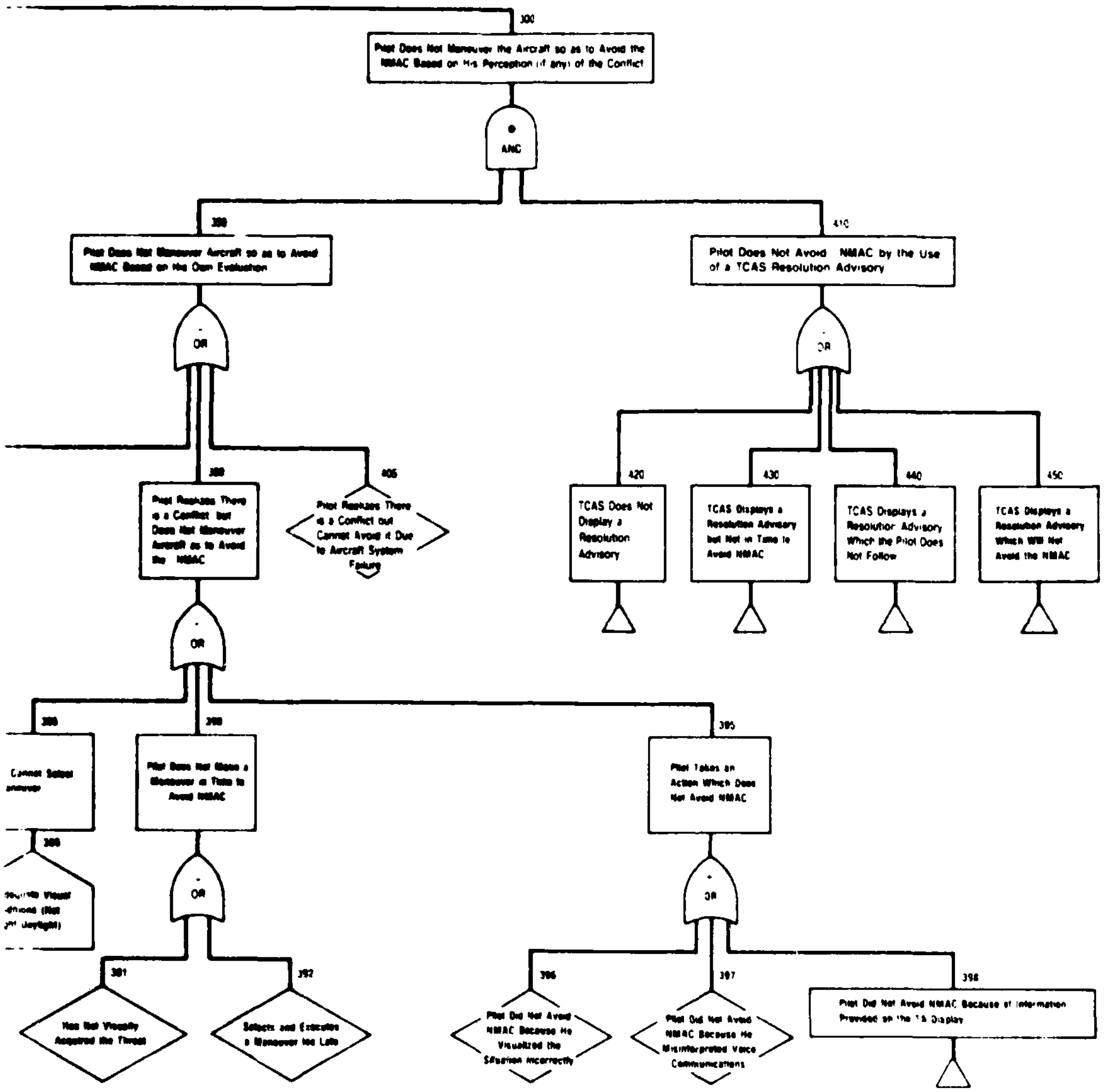
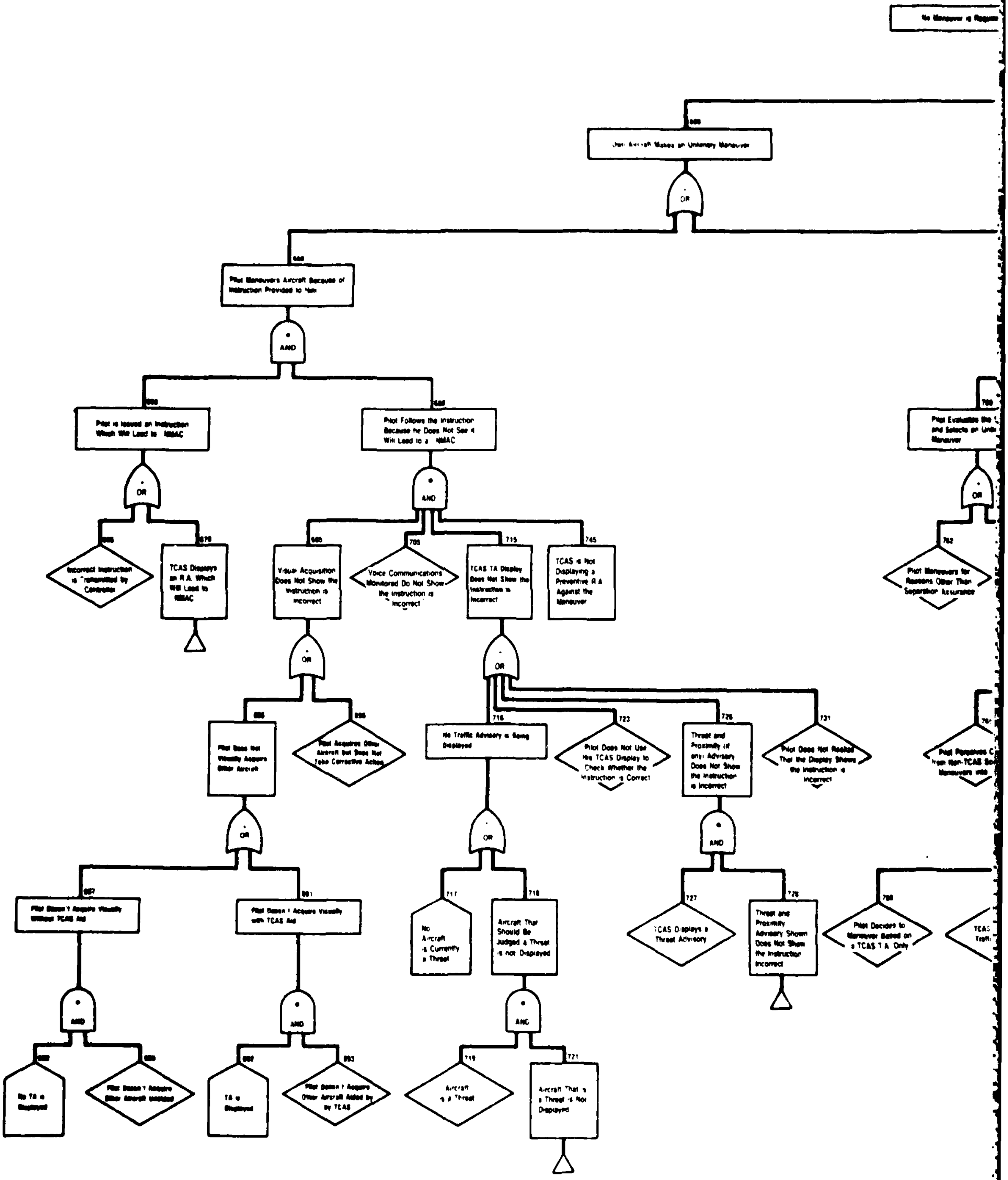


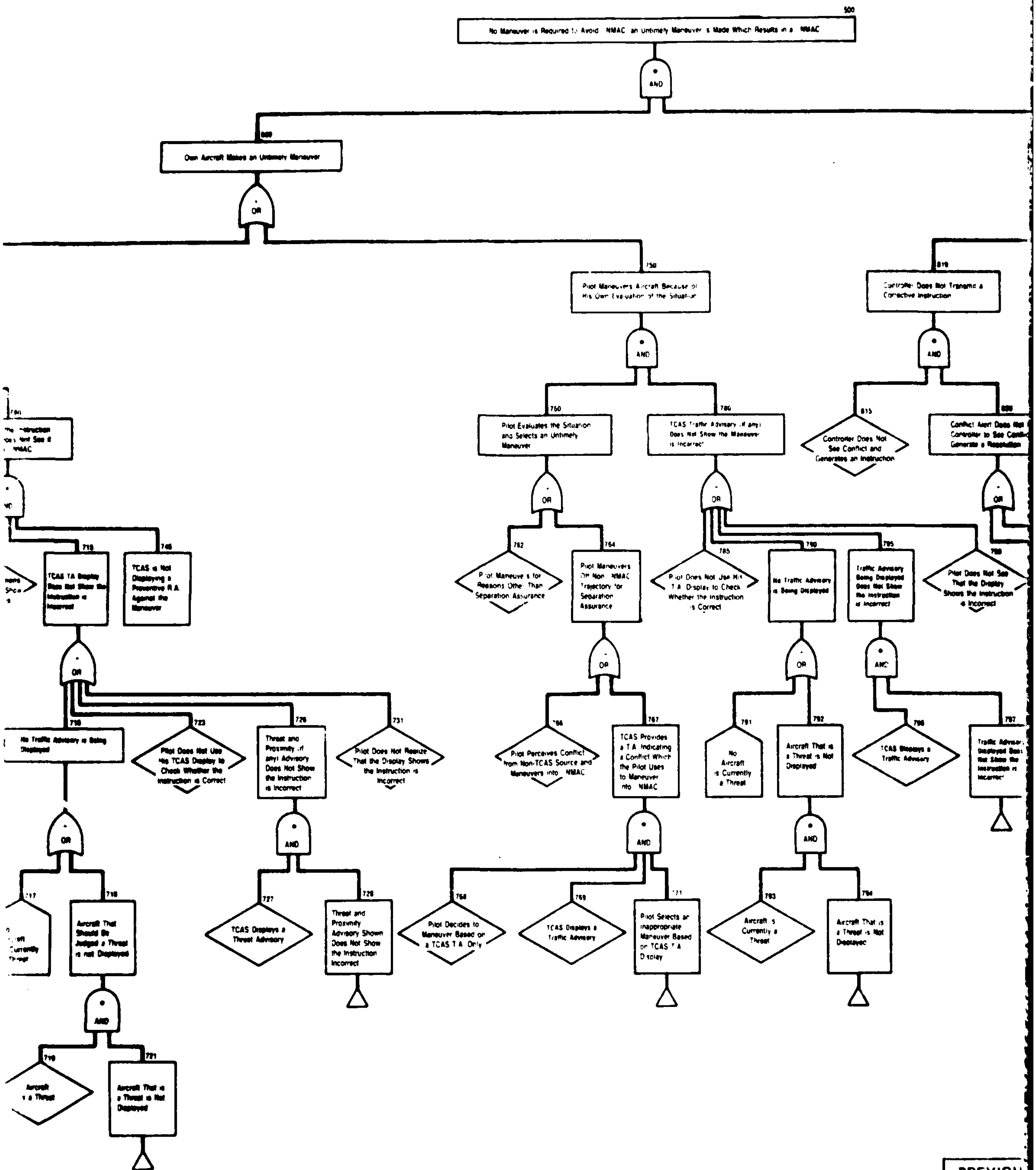

**FIGURE 2**
**TCAS FAULT TREE, BRANCH 000**
**(UNRESOLVED CRITICAL NMAC)**


Pilot Maneuvers Aircraft Because of Instruction Provided to Him
Pilot is Issued an Instruction Which Will Lead to NMAC
Pilot Follows the Instruction Because he Does Not See it Will Lead to a NMAC
Incorrect Instruction is Transmitted by Controller
TCAS Displays an R.A. Which Will Lead to NMAC
Visual Acquisition Does Not Show the Instruction is Incorrect
Voice Communications Monitored Do Not Show the Instruction is Incorrect
TCAS TA Display Does Not Show the Instruction is Incorrect
TCAS is Not Displaying a Preventive R.A. Against the Maneuver
Pilot Does Not Visually Acquire Other Aircraft
Pilot Acquires Other Aircraft but Does Not Take Corrective Action
No Traffic Advisory is Being Displayed
Pilot Does Not Use His TCAS Display to Check Whether the Instruction is Correct
Threat and Proximity (if any) Advisory Does Not Show the Instruction is Incorrect
Pilot Does Not Realize That the Display Shows the Instruction is Incorrect
Pilot Maneuvers for Reasons Other Than Separation Assurance
Pilot Doesn't Acquire Visually Without TCAS Aid
Pilot Doesn't Acquire Visually with TCAS Aid
No Aircraft is Currently a Threat
Aircraft That Should Be Judged a Threat is not Displayed
TCAS Displays a Threat Advisory
Threat and Proximity Advisory Shown Does Not Show the Instruction Incorrect
Pilot Decides to Maneuver Based on a TCAS T.A. Only
No TA is Displayed
Pilot Doesn't Acquire Other Aircraft Unaided
TA is Displayed
Pilot Doesn't Acquire Other Aircraft Aided by TCAS
Aircraft is a Threat
Aircraft That is a Threat is Not Displayed



1

2

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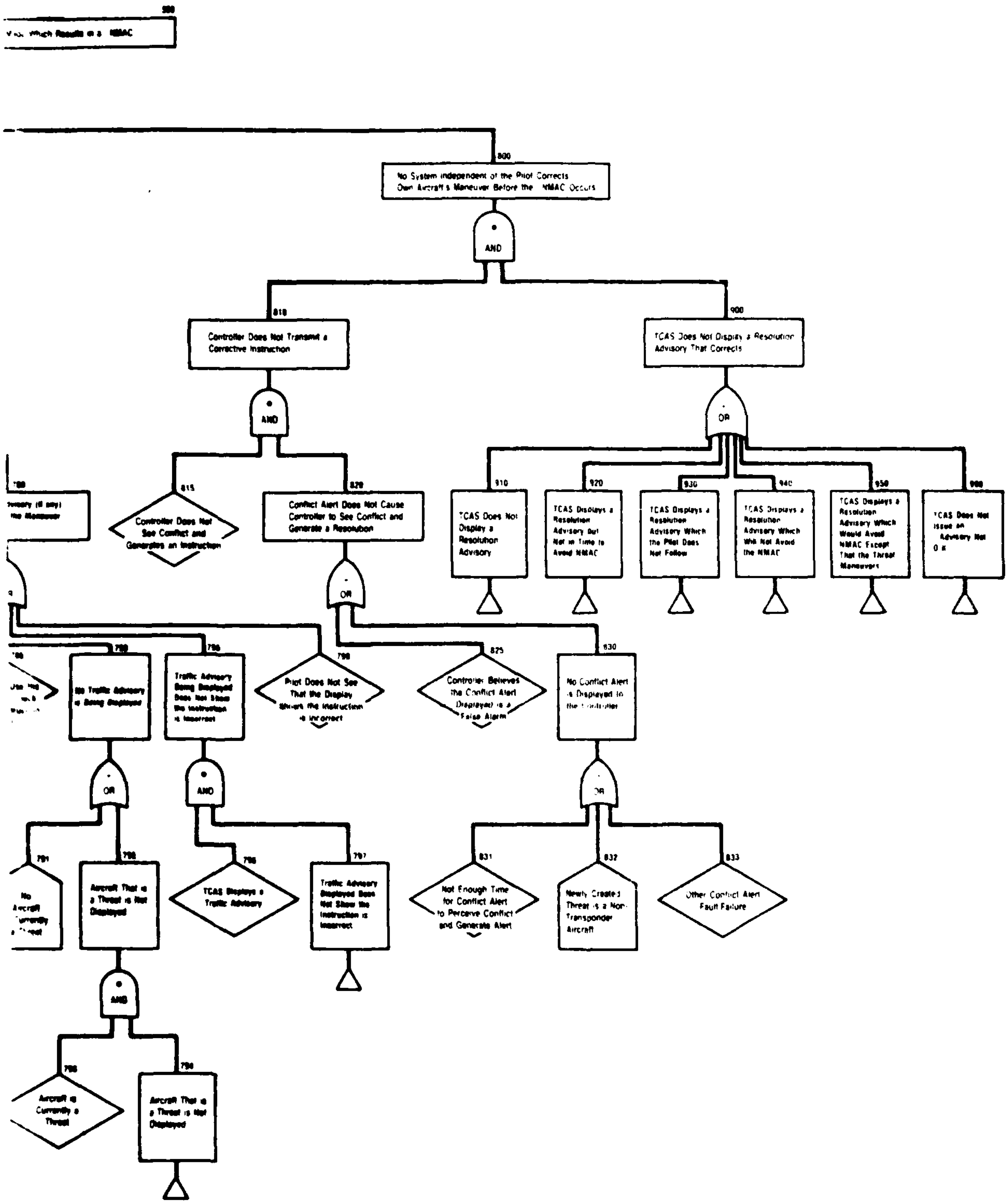


**FIGURE 3**
**TCAS FAULT TREE, BRANCH 500**
**(INDUCED CRITICAL NMAC)**



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TABLE 2
SUMMARY OF BASIC PROBABILITIES

| CONDITION PRESENT | PROBABILITY |
|---|---|
| Instrument Meteorological Conditions | .16 |
| Bright Daylight Conditions | .70 |
| GA and "other" Aircraft | .79 |
| Intruder is Transponder Equipped | .92 |
| Intruder is Mode C Transponder Equipped | .61 |
| Risk Ratio for GA Altimetry | .0317 |
| Unresolved Component | .0143 |
| Induced Component | .0174 |
| Risk Ratio for Maneuvering Intruder | .027 |
| Probability of not being tracked | |
| at time of TA | .06 |
| at time of RA | .03 |
| Risk Ratio for "Stuck C-Bit" | .002 |
| Risk Ratio for Equipment Failure | .0001 |
| Probability of not visually acquiring in bright daylight conditions | |
| by 15 s before CPA | .17 |
| by time of RA | .35 |

- VNA: The pilot visually acquires the threat, but does Not Avoid the NMAC.

- VMIR: The pilot visually acquires the threat but still Maneuvers on an Incorrect Resolution Advisory.

- Resolution Advisory (R): Expedient action, at least compatible with the RA, is necessary. Various factors may inhibit the pilot's reaction thereby failing to avoid an NMAC. This leads to the following failure:

  - RNF: The pilot does Not Follow the RA.

- Traffic Advisory (T): The intent of the TA is to alert the pilot to search for the intruder. If visual acquisition is not achieved and action is taken on the TA alone, failure may occur in one of two ways:

  - TNA: Based on his interpretation of the TA, the pilot disregards an RA or what he sees and does Not Avoid the NMAC.

  - TI: The pilot maneuvers to Induce an NMAC based on his interpretation of the TA.

These five failure mechanisms are tested as variables in the analysis.

The evaluation of the fault tree is simplified if a nominal, or baseline, set of operational conditions is assumed. Variations from these nominal conditions are then explored in a subsequent analysis of the sensitivity to these assumptions. The assumed nominal conditions are:

1. If a pilot visually acquires a conflicting aircraft, he will avoid it.

2. In absence of visual acquisition, the pilot follows the Resolution Advisory.

3. Visual acquisition, as aided by the Traffic Advisory display for Mode C aircraft, is assumed to be effective only in bright daylight.

4. The airborne traffic has today's level of transponder and Mode C equipage.

5. The intruder is not TCAS-equipped. (If the intruder were TCAS-equipped, it would have air carrier quality altimetry, and its displayed escape maneuver would be coordinated.)

6. No "false moves" are made by the TCAS pilot either from confusion or from prematurely maneuvering based on a Traffic Advisory.

7. Today's level of vigilance for see-and-avoid procedures is maintained; that is, TCAS does not cause the pilot to relax his guard.

Evaluating the fault tree proceeds with evaluating both of the major branches under these nominal conditions, to get the probability of the top event.

Unresolved NMAC (The 000 Branch)

Evaluation of this branch (called event 2-000) proceeds by setting all ATC faults to a failure probability of 1.0 (such failure is presumed to have already occurred, or the pre-existing NMAC would not be in process). We can summarize the failure modes and their relative probabilities which do not include human factors as follows:

- Encounters in which neither TA nor RA is received. This failure is primarily caused by lack of Mode C equipage levels, and is the principal failure mode for TCAS. (Probability: .41)

- Bright daylight encounters in which a TA is received, visual acquisition does not occur and an inadequate RA is generated. (Probability: .0008)

- Encounters in which a TA is received, visual acquisition is not possible, and an inadequate RA is received. (Probability: .002)

- Encounters in which a TA is not received prior to the RA, an RA is generated, but it is inadequate to avoid the NMAC. (Probability: .0004)

In addition, there are failure modes which relate to the human-factors variables as follows:

- Bright daylight encounters in which a TA is received and visual acquisition does occur before the RA, but the pilot fails to avoid the critical NMAC with probability VNA + TNA. (Probability: .259(VNA + TNA))

- Bright daylight encounters in which a TA is received and visual acquisition does not occur, an RA is generated, but the pilot fails to follow the RA with probability RNF. (Probability: .138 RNF)

- Bright daylight encounters in which a TA is received, visual acquisition occurs but not before the RA is issued. An inadequate RA is issued, and the pilot acquires the threat, but does not determine the RA to be inadequate with probability VMIR. (Probability: .0008 VMIR)

- Encounters in which a TA is received, visual acquisition is not possible, and the pilot does not follow the RA with probability RNF. (Probability: .169 RNF)

- Encounters in which no TA is received, an RA is received but is not followed with probability RNF. (Probability: .020 RNF)

The total failure rate is thus .413 + .259 (VNA + TNA) + .327 (RNF) + .0008 (VMIR).

Induced NMAC (The 500 Branch)

The failure scenarios for this event (called event 2-500), where TCAS might induce an NMAC, and their associated probabilities are:

- Encounters in which visual acquisition occurs but the pilot does not see that the RA is incorrect with probability VMIR. (Probability: .014 VMIR)

- Encounters in which a TA is received and visual acquisition is possible, but fails to occur. (Probability .0029)

- Encounters in which a TA is received, but visual acquisition is not possible. (Probability: .0073)

- Encounters in which a TA is not received. (Probability: 0.0008)

- Encounters in which a TA is received, incorrectly acted upon, and causes an NMAC (Probability: .59 TI)

The probability of event 2-500 is thus .011 + .014 VMIR + .59 TI.

Top Event

As the two major events are mutually exclusive, the two probabilities add to obtain the probability of a critical near midair collision, which is .424 plus a residual composed of human factors failures, as seen in Figure 4.

## 8. Sensitivity Analysis

Sensitivity of five basic system fault probabilities was tested in this analysis: Mode C equipage, surveillance failure, altimetry error, maneuvering intruder hazard, and human factors. To test the change in the probability of events 2-000 and 2-500 (and thus the top event) corresponding to changes in failure rates of these elements, the failure rates were varied between bounds judged appropriate for each element as follows:

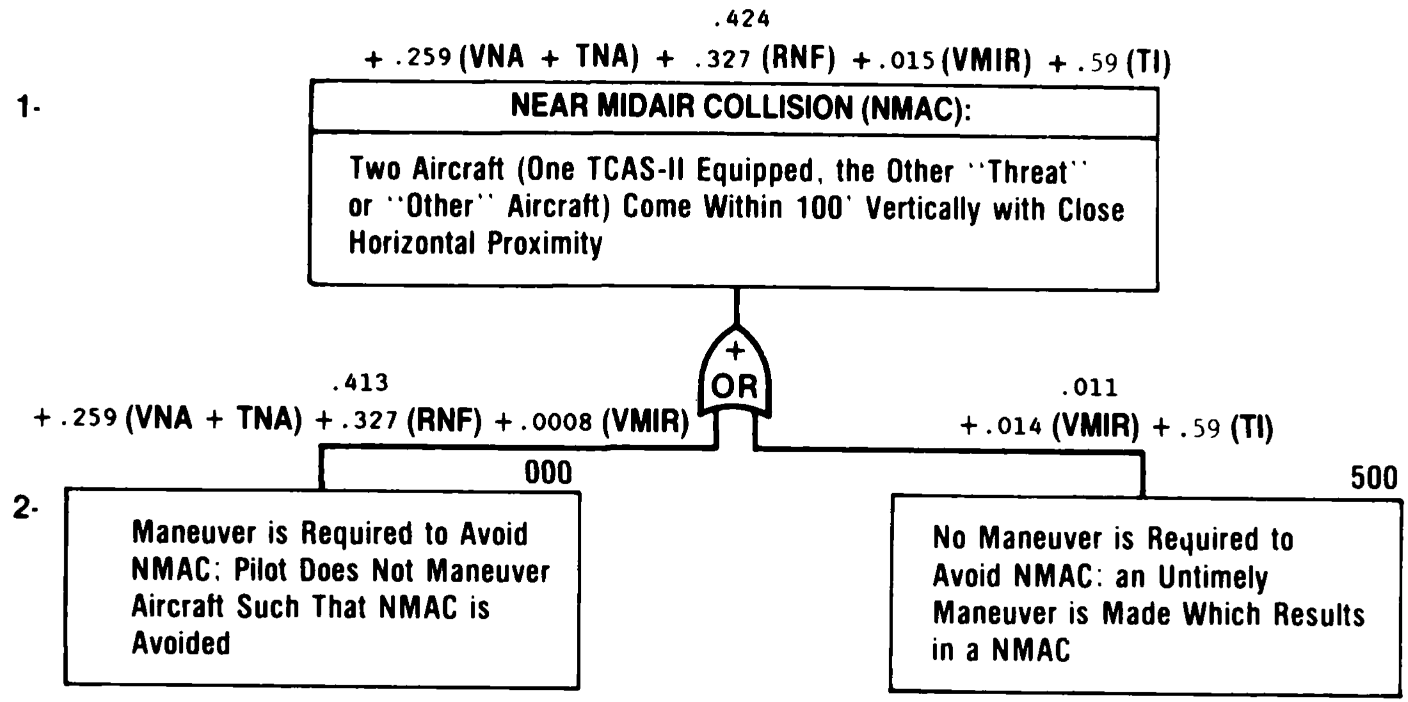



FIGURE 4
CALCULATION OF THE PROBABILITY OF TOP EVENT

- Equipage: The nominal probability for an encounter with a Mode C aircraft is .61. To test the effect of this factor, the calculations were also run assuming all aircraft Mode C equipped.

- Surveillance: The nominal surveillance track probability is .94 for a TA and .97 for an RA. This quantity was explored by alternatively improving surveillance by a factor of three and degrading it by a factor of about two (e.g., probability of receiving RA varied from .99 to .94).

- Altimetry error. The only significant component is that ascribed to general aviation aircraft (uncorrected static error). Sensitivity to this parameter was tested both by varying the standard deviation plus and minus 20 percent, and by changing the form of the distribution from Gaussian to exponential.

- Maneuvering Intruder Hazard: The overall probability of encountering an intruder that would start maneuvering in such a manner and at just the time to "fake out" the TCAS and cause an NMAC was estimated from airborne data. The sensitivity to this factor was explored by changing the maneuver probability by 50 percent, both higher and lower.

- Human Factors. In the nominal case, no pilot failure modes were accounted for, although five were identified. To give some indication of the effect of these failure modes, they were permitted to fail at the rate of 1 in 20.

Also, three basic assumptions were made in the nominal estimate: TAs were not given on aircraft that are transponder equipped, but which do not report Mode C; visual acquisition, as enhanced by the TCAS, is used to provide separation, and RAs are followed in instrument meteorological conditions (IMC). The sensitivity analysis tests the opposing assumptions: that non-Mode C aircraft are tracked, that enhanced visual acquisition is not effective, and that RAs are not followed in IMC.

Failure Probabilities

The resulting changes in probability for events 2-000, 2-500 are graphed in Figure 5 on a logarithmic scale. The lines across the bars represent the nominal probability of each event. It should be noted that a change in probability of event 2-000 is accompanied by a corresponding change in the probability of event 2-500 in most cases. For example, higher Mode C equipage results in much lower probability of an unresolved NMAC but a higher probability of an induced NMAC.

Surveillance failure has little effect on the probability of both unresolved and induced NMACs. Altimetry error and maneuvering intruder hazards have no discernable impact on unresolved NMACs, but induced NMACs are sensitive to these factors. If, instead of the Gaussian error model, an exponential error model is assumed and the failure probabilities are calculated, the effect is similar to using the Gaussian model with about a 15 percent increase in nominal error.

If TAs were to be provided on non-Mode C aircraft, there would be a significant reduction in the unresolved NMACs without an increase in induced NMACs.

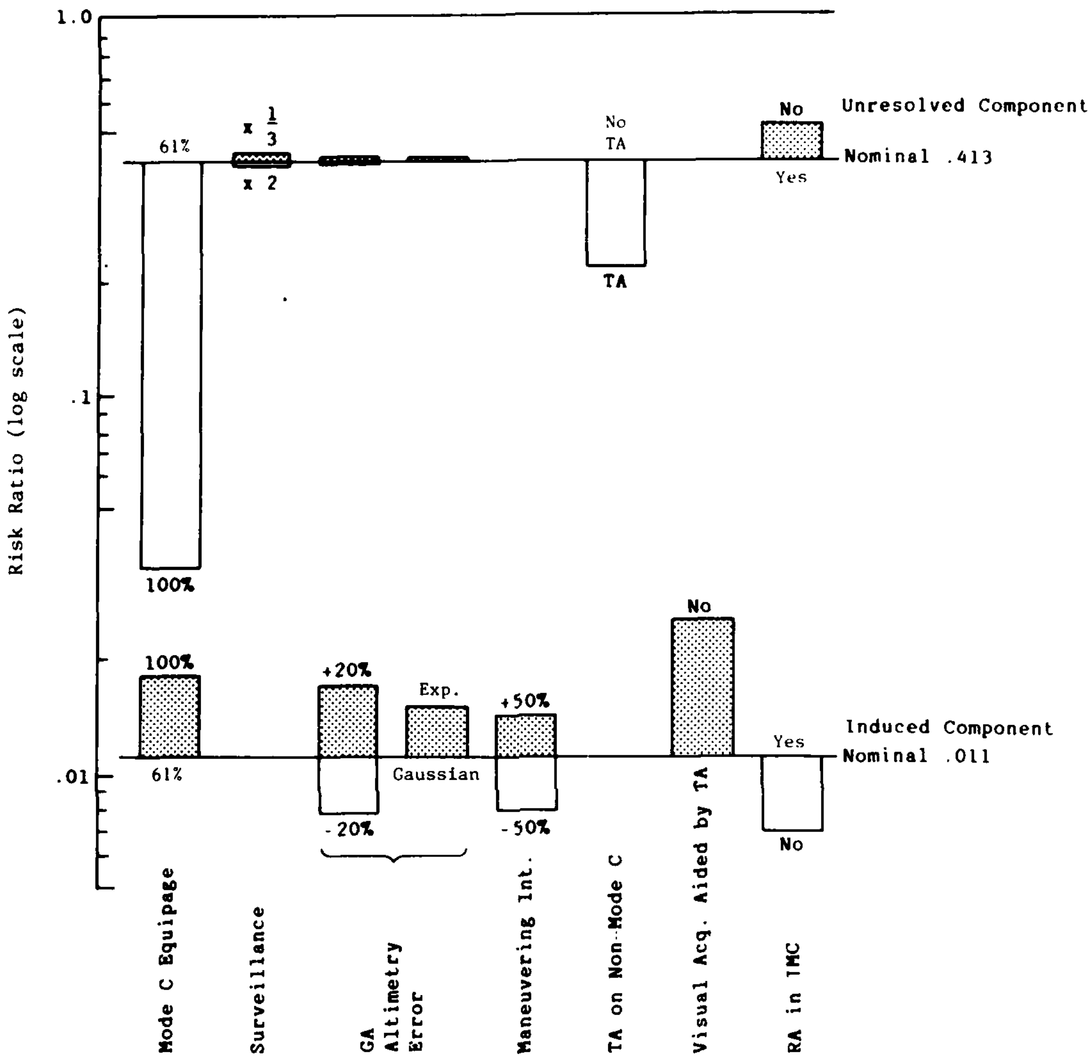



**FIGURE 5**
**INFLUENCE OF VARIOUS FACTORS ON OVERALL SYSTEM PERFORMANCE**

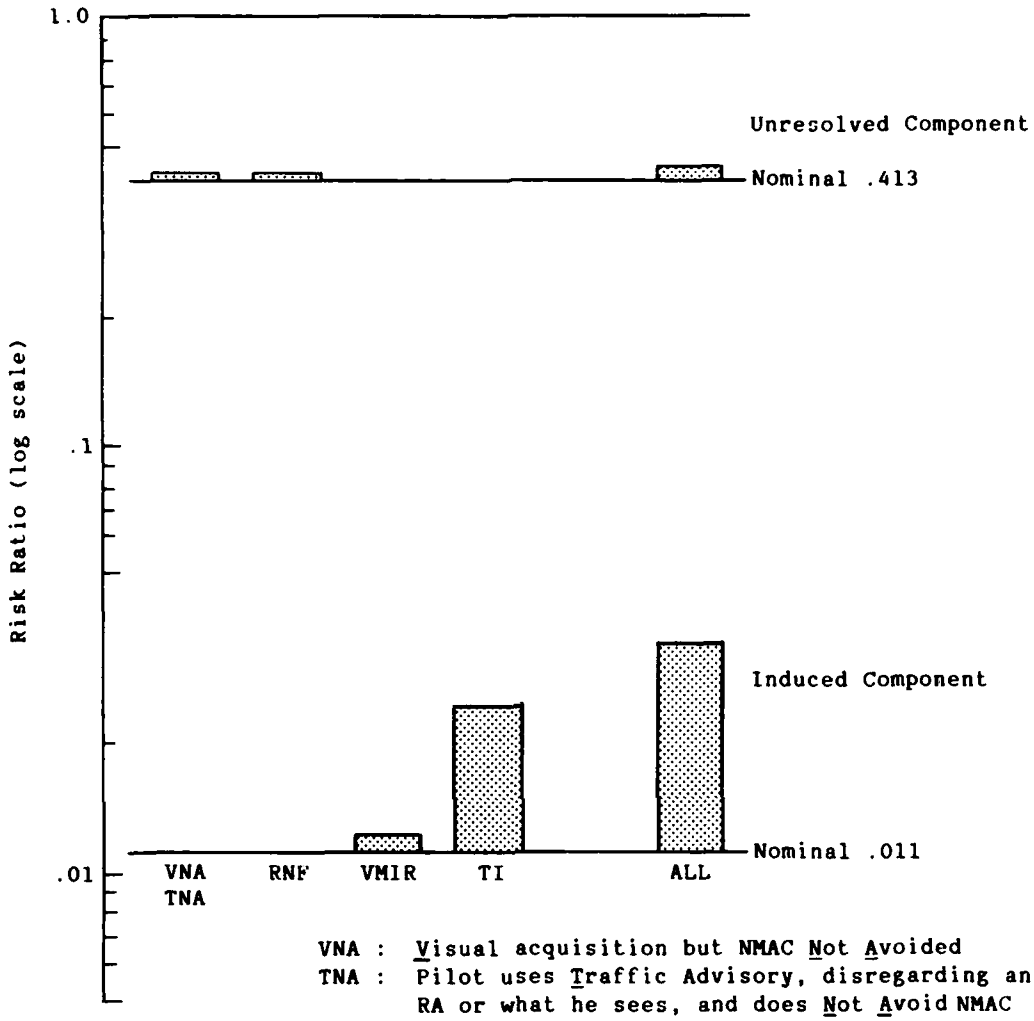
Improved visual acquisition, arising from the presentation of TAs, has little effect on unresolved NMACs. This is due to the fact that since only Mode C aircraft are tracked, there is high probability of getting an RA, given the TA; the only impact of visual acquisition is to correct inadequate RAs, which are infrequent. For induced NMACs, the benefit of improved visual acquisition can be seen by observing that, without any TAs (visual acquisition ineffective), that portion of the failure rate approximately doubles.

By not following RAs in IMC, we can avert a substantial number of induced NMACs as shown by the bar on the right side of Figure 5; however, this also increases the number of unresolved NMACs.

<u>Human Factors</u>

To obtain some indication of the effect of human factors failure modes, a failure rate of .05 (1 failure every 20 situations in which the potential for failure exists) was used. The individual failures have been broken down into their five components (VNA, TNA, RNF, VMIR, and TI) and graphed in Figure 6, using the same scale as Figure 5.

It can be seen from the graph that human factors has little impact on the unresolved component of the failure rate, which is only slightly sensitive to VNA (intruder was visually acquired but NMAC not avoided), TNA (TA misleads the pilot into disregarding a visual acquisition or correct RA), and RNF (RA not followed). The unresolved component is very insensitive to VMIR (Maneuver on an incorrect RA in spite of visual acquisition indications) because the opportunity to make this error is infrequent (.08% of all NMAC encounters). TI (use of the Traffic Advisory, inducing an NMAC ) does not apply to the unresolved component.




VNA : Visual acquisition but NMAC Not Avoided
TNA : Pilot uses Traffic Advisory, disregarding an RA or what he sees, and does Not Avoid NMAC
RNF : Resolution Advisory Not Followed
VMIR: Visual acquisition, but pilot still Maneuvers on an Incorrect RA
TI : Pilot maneuvers based on TA, Inducing an NMAC

Note: Assumed failure rate for each factor is .05; for all factors at once they are also .05.

**FIGURE 6**
**INFLUENCE OF HUMAN FACTORS ON OVERALL SYSTEM PERFORMANCE**

As for the induced component, it can be seen that the potential exists for a significant number of failures by use of the Traffic Advisory to make an incorrect maneuver which induces an NMAC. It should be noted, however, that this may be an over-estimate for the following reasons:

1. Pilot training should reduce the use of the TA for purposes other than as an aid to visual acquisition.

2. If the TA is used for maneuvering, we assumed the following conservative conditions:

    a. Visual acquisition is not attempted or is not possible

    b. If the display is accurate, the pilot must interpret it adversely and disregard any ensuing RA (actually, a chain of concurrent probabilities).

As can be seen in Figure 6, the induced component of the failure rate is not sensitive to the other factors (VMIR, RNF, TNA, or VNA).

If all five factors were to fail independently at the rate of 1 in 20, the relative probability of an NMAC would be 48.4 percent, with the unresolved component being 44.2 percent and the induced component being 4.2 percent.

## 9. Findings

The basic philosphy is to make the assessment realistic, but conservative. In particular, no credit was assumed for the following:

- Visual acquisition in less than bright daylight conditions

- Some situation checking features in the logic feature

- Aircraft leveling out gradually instead of abruptly

- The Resolution Advisory preventing an incorrect maneuver, or correcting one that may have been prematurely taken on a Traffic Advisory

The data and analyses brought to focus in this study disclose the following findings relative to the Risk Ratio.

1. Under a nominal set of baseline conditions this ratio is about 42 percent. Figure 7 shows this, with the first bar (100 percent) as the pre-existing risk of encountering a NMAC without TCAS; the second bar (Risk Ratio is 42 percent) is the risk of encountering an NMAC with TCAS under the nominal conditions. Most of this residue is attributable to the lack of complete equipage with altitude reporting transponders.

   If the capability to track all non-Mode C aircraft and display an "altitude unknown" Traffic Advisory were added to the nominal system, a major reduction in the unresolved component of the Risk Ratio would be obtained; the residue would decrease to about 25 percent, as shown in the third bar of Figure 7. This is caused by the improved visual acquisition that would result for those aircraft that are on a near collision course.

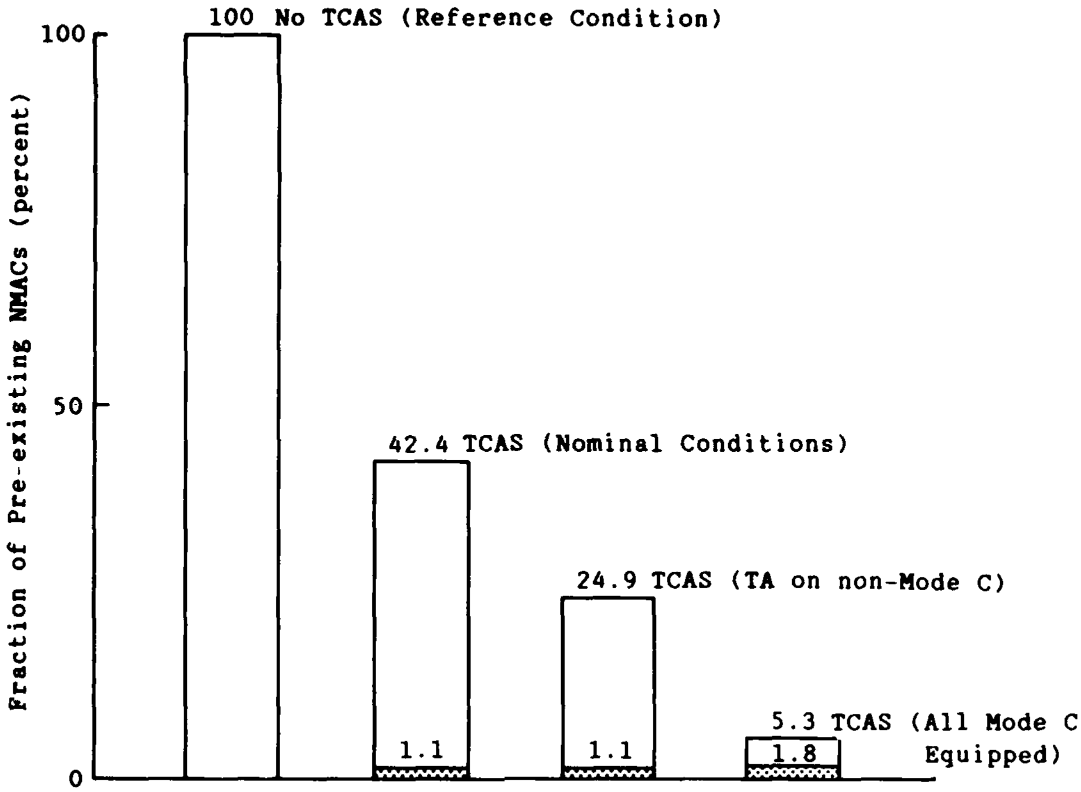



**FIGURE 7**
**RELATIVE TCAS EFFECTS**

The greatest payoff, however, in reducing the risk of NMACs would be to increase the number of aircraft having altitude reporting transponders. Statistics on avionics show the trend to be in that direction. If all aircraft were equipped with altituding reporting transponders, the Risk Ratio would decrease to 5 percent (the fourth bar of Figure 7), two thirds of which is attributable to surveillance limitations; the remainder is attributable to maneuvering intruders and to altimetry error.

2. Most of the residue under nominal conditions is caused by an inability to avoid an NMAC that would have occurred even without TCAS (the unresolved component of Risk Ratio). Under certain conditions, however, the system itself can induce an NMAC (the induced component of Risk Ratio). The risk of that occurring for the nominal conditions is about one percent of the risk encountering an NMAC without TCAS (shaded parts of the bars in Figure 7; see also Table 3). The primary cause for these failures are altimetry errors and sudden maneuvers by the intruder.

   If the standard deviation (Gaussian distribution) of general aviation altimetry error were to be 20 percent larger than estimated, the induced component of Risk Ratio would increase to about 1.7 percent. While this component is small relative to the unresolved component, and the overall effect on Risk Ratio is small, the minimization of induced NMACs is in itself a major TCAS objective. If the assumed error distribution were characterized by the heavy tailed symmetrical-exponential distribution instead of the Gaussian, the nominal induced component of Risk Ratio would

TABLE 3
SENSITIVITY TO VARIOUS FACTORS

| CONDITION | OVERALL RISK RATIO (Percent) | UNRESOLVED COMPONENT (Percent) | INDUCED COMPONENT (Percent) |
|---|---|---|---|
| Nominal | 42.4 | 41.3 | 1.1 |
| Non-Mode C Traffic Advisories | 24.9 | 23.8 | 1.1 |
| 100 Percent Mode C Equipage | 5.3 | 3.5 | 1.8 |
| 20 Percent Higher GA Altimetry Error | 43.4 | 41.7 | 1.7 |
| Exponential Altimetry Error Model | 43.1 | 41.6 | 1.5 |
| 50 Percent Increase in Probability of Fake-Out Maneuver | 42.8 | 41.3 | 1.4 |
| Probability of Missed Surveillance. 30 Percent of Nominal | 41.0 | 39.9 | 1.1 |
| Aided Visual Acquisition Not Effective | 44.1 | 41.6 | 2.5 |
| TCAS Not Used in IMC | 51.4 | 50.7 | .7 |
| Human Factor Failures: One Per 20 Encounters | 48.4 | 44.2 | 4.2 |

be 1.5 percent -- somewhat larger than before but similar in effect.

The contribution of altimetry error to the total overall Risk Ratio is dominated by the GA errors; the hazard caused by air carrier errors is at least an order of magnitude lower. A reduction of the GA altimetry error provides more than proportionate reduction in the induced component of the Risk Ratio.

The risk of two air carriers, both equipped with TCAS, having an NMAC is several orders of magnitude less than without TCAS; altimetry is corrected, maneuvers are coordinated, and both aircraft have surveillance.

3. TCAS is susceptible to being thwarted, in certain cases, by an intruder making a sudden vertical maneuver. The situation of most concern is one in which an intruder with a substantial vertical rate approaches a level TCAS aircraft so as to project a crossing through its altitude. A vertical escape initiated by the TCAS aircraft could be thwarted ("faked out") if the intruder were suddenly to level off at a critical time and altitude. The study used actual aircraft data from Piedmont flights and from FAA flights to estimate the contribution of this factor to overall Risk Ratio. A 50 percent increase in the probability of a fakeout maneuver will cause a nearly proportionate increase in the induced component (increases the induced component of Risk Ratio from 1.1 percent to 1.4 percent).

4. The nominal performance of surveillance quality was estimated from live track data in many regions of airspace. If the missed track rate were to decrease from its nominal rate of three percent to one percent, a small improvement in the unresolved component of Risk Ratio would be obtained; the induced component is essentially unaffected.

5. A Traffic Advisory is displayed on an intruder approximately 15 seconds before the Resolution Advisory is posted. This precursor is intended to alert the pilot to start a visual search for an aircraft that may be of concern. If visual acquisition is obtained, an incorrect Resolution Advisory, such as from altimetry error, can be overriden by the pilot. This aided acquisition reduces the induced component of Risk Ratio by more than half. Very little effect occurs for the unresolved component, as a Resolution Advisory almost always occurs if a Traffic Advisory is present.

6. If TCAS is not used in IMC, which constitutes roughly 16 percent of the NMACs, the unresolved component would correspondingly increase, and the induced component would correspondingly decrease.

7. The probability of encountering an NMAC in today's environment, in the absence of TCAS, is approximately once in 100,000 hours of flight. Four quite different approaches to obtaining this estimate were used, and they were all within 4:1 of this value.

8. Five pilot failure modes (human factors) were postulated and their relative impact parametrically assessed. The most severe failure postulated (TI) is one in which the pilot used the Traffic Advisory for maneuvering rather than for visual acquisition, made an inappropriate maneuver, and disregarded any subsequent Resolution Advisory. The second most severe human factor failure is one in which the Resolution Advisory is simply not followed.

   If all five human factor failures were to fail independently at the rate of 1 in 20, the Risk Ratio would be about 48 percent, with the induced component accounting for 4.2 percent.

## 10. Conclusions and Recommendations

### Operational Implications

Operational discipline for the use of TCAS will vary depending on many factors. However, it was found that: (1) visual acquisition, as aided by the Traffic Advisory display, can play an important role both in improving see-and-avoid and in minimizing the effects that would induce critical NMACs, (2) alertness remains necessary in visual conditions both to protect against aircraft not equipped with transponders and, to a much lesser extent, to protect against equipped aircraft which may be missed by TCAS surveillance.

If TCAS is not used in IMC, the induced component of NMACs would decrease; however, the larger benefit of being able to resolve NMACs in IMC would also decrease.

## Training Implications

During the course of this System Safety study, several factors that should be addressed in a training and proficiency program became apparent.

1. Traffic Advisories are intended to aid visual acquisition and to prepare the pilot should a Resolution Advisory follow. Premature maneuvering based on the Traffic Advisory alone could be self defeating.

2. Prompt reaction when a Resolution Advisory is posted is important. In order to be able to maneuver through the uncertainties of altimetry error, a displacement on the order of 400-500 ft may be necessary (larger at high altitudes). A delayed reaction will reduce the displacement achievable in the available time.

3. From the results of the study it appears that the pilot is statistically better off by trusting his instrument than by not trusting it--the ratio of resolving NMACs to inducing them is 23:1. If, in addition, Traffic Advisories are used to aid visual acquisition, this ratio increases to 58:1.

## Equipment Reliability Implications

The type of equipment failure of concern for this study is one which could cause an NMAC. If one occurs which does not cause the performance monitor to immediately turn off TCAS, it should be at the rate of $10^{-4}$, or less, per NMAC to be negligible relative to other causes. The performance monitor therefore needs to be effective in detecting critical sources of failure in the elements of the TCAS system.

## Program Implications

The System Safety study highlighted several recommended areas that the TCAS Program might emphasize in the future.

1. Steps should be initiated to confirm applications of TCAS in IMC. A determination of the detailed nature of altimetry and of maneuvering intruders under poor visibility conditions should be obtained and methods explored for controlling them.

2. Identify steps that might be undertaken to remove out-of-tolerance altimeters from the system.

3. Develop pilot training measures to specifically treat human-factor failure modes that have been identified. Consider means to verify the effectiveness of such steps.

## Changes Required

This study resulted in an intensive evaluation of all safety-related parameters and procedures. It was concluded that an increase of the ALIM parameter at low altitudes appears desirable. This would decrease the effects of altimetry error and would not affect the alarm rate significantly.

# 1. INTRODUCTION

## 1.1 Purpose of the Study

The aircraft Traffic Alert and Collision Avoidance System (TCAS), which provides vertical-plane resolution advisories, is designated minimum TCAS II. TCAS (Reference 1), developed in response to a widely perceived need to provide the pilot with an independent, back-up collision avoidance system, is in the final phase of its development and operational evaluation in a commercial air carrier.

Because TCAS is intended to provide emergency information to the pilot in time to avert an impending collision, a quantitative evaluation of its performance, advantages and limitations with respect to the improvement of aviation safety is essential; the TCAS System Safety study was performed to satisfy this need. U.S. airspace already has many levels of "separation assurance" built into the Air Traffic Control (ATC) system--"see-and-avoid" procedures, flight plan clearance, ATC surveillance, Conflict Alert at the ATC facility, and an impressive array of redundant systems and fall-back procedures. The TCAS equipment and procedures must be compatible with this environment.

The airspace environment introduces three major limitations to TCAS effectiveness that must be assessed:

- The effect of using TCAS in an environment where some aircraft do not have ATC transponders.

- The effect of instrumentation and calibration errors in altimetry measurement and reporting.

- The effect of an intruder making sudden maneuvers, especially ones which would thwart a TCAS Resolution Advisory.

Each of these not only can render the TCAS ineffective, but of more concern, they can cause TCAS to make the situation worse than before. In addition to these limitations there are the more conventional failure mechansisms: avionics failures, software failures, misinterpretation of displays, failure to respond, etc. It is necessary to quantitatively assess the magnitude of each factor, uncover interrelationships among system elements, and make those recommendations which will minimize the effects of any safety related faults.

## 1.2 Methodology

### 1.2.1 Study Approach

A System Safety study is an overall assessment of the interrelation of all factors pertinent to system performance--TCAS avionics, the pilot, the other aircraft, and the ATC system. Performance of the System Safety study required the development of analytical techniques and simulation modeling, plus the analysis of flight test data and historical data, to provide a sound technical basis for the study. The study uses the "fault tree" technique to structure a "top down" analytical approach (Reference 2). This begins with the undesired event (a near midair collision) at the top of the logical tree and systematically branches down to the root causes (faults) of the undesired top event. The approach was channelled into three major areas:

a. Definition — Systematic description, using fault tree techniques, of all possible ways in which failure could occur.

b. Qualification — Analysis of the TCAS fault tree to determine which failure modes are most important and which are less likely or unlikely to occur.

c. Quantification — An analysis of the predominate failure mechanisms is conducted to determine their probability of occurrence. The computation of overall system risk follows directly.

In addition, the active participation of the aviation community was seen to be a necessary means to assure that all important aspects of System Safety were addressed. The following approach was taken in the course of the study to coordinate these elements:

- A study team was formed among personnel from the FAA, MITRE, and M.I.T. Lincoln Laboratory. This team developed the analysis and data reduction required to perform the System Safety study, and provided periodic progress briefings.

- Members of the aviation community, together with FAA and DoD representatives (Appendix A), were invited to participate in the review of the briefings. Five progress briefings were held during the course of the study.

The TCAS System Safety study would not have achieved the results presented in this report without this in-process review, particularly of the private sector reviewers who were more than generous in their contributions of time and effort. By their questions and comments during the course of the study, these individuals and the organizations they represented helped assure that the study focused on the critical issues and that important issues were not overlooked.

### 1.2.2 Study Assumptions and Limitations

The TCAS System Safety study has been structured broadly enough to be applicable for analysis of the minimum TCAS II system in all traffic situations and environmental conditions that are expected in normal flight. Whenever possible, the parameters used in the study were derived from TCAS test flight data. In particular, the vertical rates, altitude separation, slant ranges and advisory rates used to describe the airspace are derived from flight test data, with particular emphasis on the Phase I Operational Evaluation tests conducted with Piedmont Airlines (normal air carrier operation on an IFR flight plan). A TCAS installation for VFR operation, such as onboard general aviation aircraft, might be quite different and is not treated here.

In the analysis of the effects of the system errors, the parametric effect of failure rates and error magnitudes is given for all major error sources. Altimetry error is assumed to follow a Gaussian distribution, and the magnitude of this error for particular classes of aircraft is derived from the available data. These assumptions are tested to determine the sensitivity of their effects on the results. Indeed, the basic analysis used conservative assumptions and subsequently tested these assumptions so that the underlying effects could be made apparent.

Failure mechanisms related to human factors are also defined. These pilot-related failures are difficult to assess since no appropriate data base exists at present. Accordingly, these factors are defined as variable terms in the analysis of the fault tree, and their effects are noted parametrically, and compared with the effects of other failure mechanisms.

The analysis performed in this study includes all the underlying ATC processes as they exist at present; however, it does not account for any interaction between the TCAS flight crew and the ATC system during the period of the TCAS alert. Such interaction, for example, could involve calling ATC for advice when a Traffic Advisory is received.

### 1.2.3 Criteria

The principal criterion for performance is simply the probability of encountering the top-level undesired event--a near midair collision. The choice of a near midair collision (NMAC) rather than simply a midair collision is made both to introduce an element of conservatism and to be able to utilize a substantial data base for the calculations. The FAA defines three classes of NMAC in Reference 3, which is quoted as follows:

"1. Critical: a situation where collision avoidance was due to chance rather than an act on the part of the pilot. Less than 100 ft of aircraft separation would be considered critical.

2. Potential: an incident which would probably have resulted in a collision if no action had been taken by either pilot. Closest proximity of less than 500 feet would usually be required in this case.

3. No Hazard: when direction and altitude would have a midair collision improbable regardless of evasive action taken."

For this study, we will use the definition of critical NMAC to quantify our results. Thus, an NMAC is one in which the aircraft pass within 100 ft vertically and close horizontally (approximately 500 ft).

Basically we are interested in evaluating the question, "Is one better off with TCAS than without it?" The measure of this question is determined by evaluating the risk of encountering an NMAC with TCAS, and dividing that by the risk of encountering an NMAC without TCAS. This quantity is defined as the "Risk Ratio". Later sections of this report will evaluate Risk Ratios of individual fault mechanisms and combine them appropriately to obtain the overall Risk Ratio. Fortunately, it was found to be possible to compute the Risk Ratio directly and so to be able to evaluate the net impact of TCAS on the safety of flight, without being too concerned about determining the precise current level of risk in the absence of TCAS.

### 1.3 Structure of the Report

Section 2 of this report provides a brief overview of TCAS, pertinent considerations in its design, operating characteristics, and displays. Section 3 describes the pertinent information, abstracted from several data sources, upon which the analyses in Section 4 and 5 are based. Section 6 evaluates the role of visual acquisition (see-and-avoid). These elements are all brought together in the fault tree of Section 7. Section 8 assesses the sensitivity of the evaluation to variations in the component factors. The key findings of the study are presented in Section 9, followed by the conclusions and recommendations in Section 10.

## 2. BRIEF OVERVIEW OF TCAS

The subject of this safety study is the minimum TCAS II system described in the Minimum Operational Performance Standard of the Radio Technical Commission for Aeronautics (RTCA), including the functions of high density operation, bearing estimation, and display of Traffic Advisories. This section gives a brief summary; considerable detail will be found in Reference 1.

### 2.1 The TCAS Concept

The TCAS concept provides a family of airborne collision avoidance services based upon the processing of ATC transponder replies from proximate aircraft. TCAS provides airborne collision avoidance services without the need for ground equipment. TCAS capabilities range from a minimal warning system, designated as TCAS I, to a full capability traffic advisory and resolution advisory system, designated as TCAS II. TCAS II is capable of operating in high density terminal areas. The minimum TCAS II provides for maneuvers only in the vertical plane; enhanced TCAS II is expected to provide for maneuvers in the horizontal plane as well as the vertical plane.

TCAS equipment will generate Traffic Advisories and Resolution Advisories when in conflict with other TCAS aircraft, as well as with other intruders equipped either with today's conventional transponder or with a Mode S transponder.

### 2.2 Minimum TCAS II Overview

The minimum TCAS II uses active interrogation of ATC transponders to track nearby aircraft in slant range and relative altitude; it uses these to assess the collision threat potential and to generate appropriate collision avoidance advisories.

The minimum TCAS II is designed to have a nominal surveillance range of 14 nautical miles over which it tracks transponder equipped aircraft in range and altitude. An on-board direction finding antenna is used to measure intruder bearing. Transponders are interrogated in discrete address Mode S or Mode C-Only All Call signal formats approximately once every second. The low duty cycle, directional interrogation and an automatic interference limiting capability prevent any operationally significant impact on the ground ATC surveillance system.

TCAS II provides the pilot with Traffic Advisories and with Resolution Advisories. In collision encounters, the system design assures that the Traffic Advisory normally occurs approximately 15 seconds before the Resolution Advisory. The Traffic Advisory can be presented on a weather radar CRT display in a graphical format which provides the range, bearing, and relative altitude of the potential threat.

As an option, non-Mode C aircraft may also be tracked. If an intruding aircraft is not reporting altitude through its transponder, it is not possible to determine if the aircraft is a potential collision threat. Therefore, for intruders not equipped with altitude reporting transponders, TCAS II may generate Traffic Advisories but will not generate Resolution Advisories. However, if the aircraft were on near collision course, such Traffic Advisories would enhance visual acquisition.

An aircraft is declared to be a collision threat to the TCAS II aircraft if either its current position, or its projected position, simultaneously violate range and relative altitude criteria. Generally, an aircraft will be declared to be a collision threat 20-30 seconds before closest approach, at which time a Resolution Advisory is displayed. This provides time for an escape maneuver by the pilot.

The Resolution Advisory is chosen to provide a specific margin of separation with a minimum change in the existing flight path of the TCAS II aircraft. The minimum TCAS II utilizes maneuvers in the vertical plane only. The Resolution Advisories can be displayed on a modified instantaneous vertical speed indicator. Positive advisories can be indicated by lighted arrows, and negative and speed limit advisories can be indicated by lighted curved bars which define the regions of vertical speeds that are to be avoided.

Before the Resolution Advisory is selected, a coordination exchange is made with the threat aircraft if it also is TCAS II equipped. Coordination ensures that complementary Resolution Advisories will be displayed and that both TCAS II maneuvers will increase separation between the aircraft. For example, one aircraft would have a climb advisory, the other a descend advisory. The escape maneuvers are designed so that sufficient separation is generated if only one of the aircraft follows the advisory.

If the threat aircraft is equipped with the TCAS I system, a crosslink Traffic Advisory message is sent providing TCAS I with the relative position of the TCAS II aircraft as seen by TCAS I. This message is transmitted when TCAS II displays its

Resolution Advisory, and is continuously updated throughout the encounter.

TCAS II threat detection and resolution logic thresholds are chosen to assure adequate separation and an acceptable alarm rate under various conditions of flight. This function is called sensitivity level control. The sensitivity level of the TCAS II logic is described by a single parameter that ranges from 1 to 7. Higher sensitivity level values provide more warning time for collision avoidance by effectively establishing a larger protection volume around the TCAS II equipped aircraft. In areas of high traffic densities, large protection volumes can lead to high alarm rates. Therefore, lower sensitivity level values are used in high density areas to reduce the protection volume and the alarm rate. Values of sensitivity level can be selected by a number of means; such as by pilot control, by automatic control based on TCAS aircraft barometric and radar altitude, and by data link command from Mode S ground stations.

## 2.3 Collision Avoidance Algorithms

TCAS II performs its aircraft separation assurance function by displaying Traffic Advisories to the pilot for potential collision threats, and Resolution Advisories for maneuvers to increase separation. The TCAS II Collision Avoidance Algorithms use the tracks formed by the TCAS II surveillance function to make this determination. The principal functions of the TCAS II collision avoidance algorithms are threat detection, resolution, and communication and coordination.

All airborne, altitude-reporting aircraft that are tracked by TCAS II are considered intruders. TCAS II evaluates each intruder through a prescribed sequence of tests to declare the intruder a threat or a non-threat. The characteristics of an intruder that are examined to determine if it is a threat are its altitude, altitude rate, range and range rate.

TCAS II generates Resolution Advisories for all intruders declared threats. Each threat is processed individually for selection of the appropriate Resolution Advisory based on track data and coordination with other TCAS II equipped aircraft. Coordination communications involve the air-to-air transmission of maneuver selections to assure the display of compatible Resolution Advisories.

### 2.3.1 Threat Detection

TCAS measures range to the tracked aircraft, and receives the altitude of the tracked aircraft in the transponder reply. Filtering algorithms derive range rate and altitude rate from the sequence of replies. Each aircraft track is tested once per second to determine whether the collision threat criteria are passed.

To be considered a collision threat, the tracked aircraft must be threatening (i.e. converging or already very close) in both range and altitude. The convergence test accounts for a wide spread of speeds by testing the time remaining until closest approach, determined by dividing range by range rate, and by testing a similar ratio for altitude. The altitude test is augmented by a projection of the vertical miss distance expected at the time of closest approach, so that an unnecessary alarm is avoided if the two aircraft are diverging vertically.

Traffic Advisories are determined using similar tests, but with a larger protected volume. This is achieved by using larger threshold values for altitude, range, and time to closest approach. For a potential collision encounter, a Traffic Advisory is displayed approximately 15 seconds before the Resolution Advisory is displayed. The intent of the Traffic Advisory is to alert the pilot to start a visual search for the intruding aircraft.

### 2.3.2 Resolution Advisory

#### 2.3.2.1 Sense Selection

When a tracked aircraft is first declared a threat, TCAS selects its sense (upward or downward) for intended resolution. This is determined by predicting the result of potential "Climb" and "Descend" escape maneuvers. The threat is projected to continue its current vertical rate, and the sense giving larger vertical separation *at the closest point* of approach is selected. The modeled escape maneuvers assume an escape rate of 1500 feet per minute, unless the TCAS aircraft already has a greater vertical rate in the direction of escape being considered. In that case, the existing vertical rate is used for the prediction.

In a conflict involving two TCAS aircraft, the first to detect the conflict selects a resolution sense as described above, and sends notice of its choice to the other aircraft using the air-to-air link. The other TCAS then selects the complementary sense, ensuring a compatible escape. A protocol that tests the discrete addresses of the aircraft transponders is used to resolve encounters in which both TCAS units simultaneously attempt sense selection.

#### 2.3.2.2 Advisory Selection

After the sense (upward or downward) of a resolution advisory has been selected, TCAS determines which of its advisories (see below) will provide adequate vertical separation (the value of the parameter ALIM) with minimum change of flight path.

| Upward Sense | Downward Sense |
|---|---|
| Climb | Descend |
| Do not descend | Do not climb |
| Do not descend faster than 500 fpm | Do not climb faster than 500 fpm |
| Do not descend faster than 1000 fpm | Do not climb faster than 1000 fpm |
| Do not descend faster than 2000 fpm | Do not climb faster than 2000 fpm |

TCAS reevaluates its Resolution Advisory once per second. The strength of the advisory may change as the encounter progresses. TCAS minimizes such transitions, with its primary consideration being adequate vertical separation, and its secondary consideration being the disruptive effects of Resolution Advisory transitions and excessive escape maneuvers. When the collision threat criteria are no longer satisfied, TCAS removes its Resolution Advisory.

## 3. CHARACTERIZATION OF TCAS ENVIRONMENT

Obviously, the operational performance of TCAS depends on the airspace in which it is used. In en route positive control airspace, the performance can be expected to be quite different from uncontrolled airspace near a terminal having a high degree of VFR traffic. For this study, the TCAS will be evaluated for an air carrier aircraft operating its normal routes on an IFR flight plan. It is typified by the routes, airspace, and traffic encountered by flights conducted by Piedmont Airlines as they carried the TCAS equipment for four months in the Fall of 1981 and Winter of 1982.

To characterize the environment, the following sources of data were used:

- Incident reports on Near Midair Collisions (NMAC) collected by the FAA
- TCAS data recorded on the Piedmont Phase I flights every time a Traffic Advisory or Resolution Advisory occurred
- TCAS operations as recorded on the FAA B727 aircraft in flights at Atlantic City, Washington, and Chicago
- Information and data on altimetry errors

The following subsections will discuss these sources of data and the inferences to be drawn from them.

### 3.1 Incident Reports on Near Midair Collisions (NMAC)

The FAA Office of Aviation Safety (ASF-200) collects and maintains reports of near midair collisions as well as of actual collisions (Reference 3). The value of the NMAC incident reports for a study such as this is that there are many more of these incidents than there are of collisions. This provides a small but sufficient sample for characterizing the TCAS environment. The FAA's coded data base goes back to 1973. In 1981 a new format was instituted. As a result, a data set was established for the years 1973-1980, and will be used for most of this analysis.

The NMAC data base provides information on the following items:

- The altitude distribution of these encounters
- The visibility conditions under which they occurred
- The operator of the other aircraft (at least one of the aircraft will be air carrier IFR)
- The fraction of transponder and Mode C equipage in the encounters
- The risk of encountering an NMAC

### 3.1.1 Altitude Distribution

The NMACs for air carrier aircraft flying on IFR flight plans occurred at various altitudes. Figure 3-1 shows the frequency of occurrence with altitude for the 105 of those incidents in the 8-year data base. While some of these occurred at high altitudes, 36,000 ft being the highest, most (71 percent) occurred below 10,000 ft. This suggests the conclusion that flight in the terminal area is the phase of most concern.

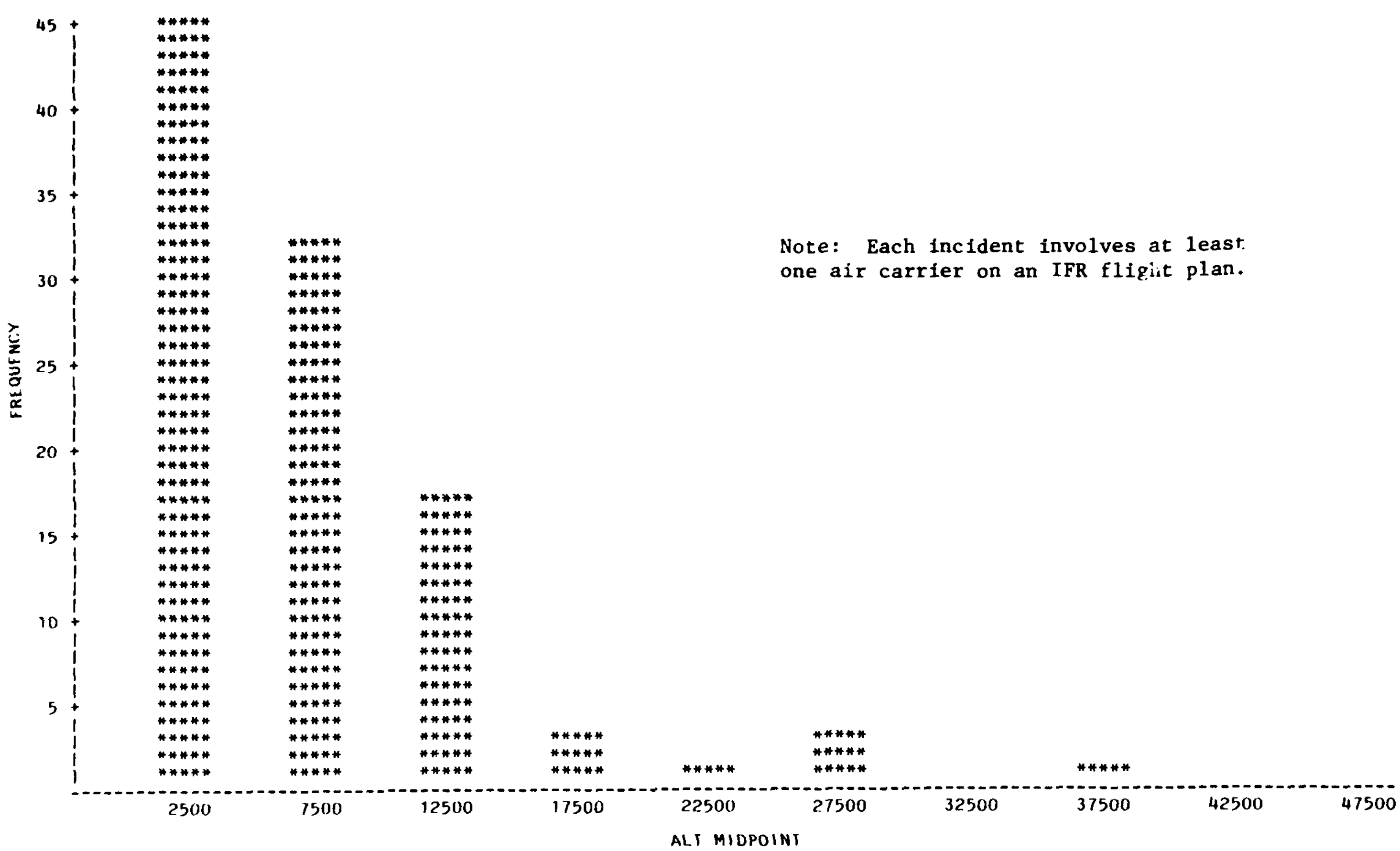



**FIGURE 3-1**
**ALTITUDE DISTRIBUTION OF NMACS**

### 3.1.2 Visibility Conditions

The visibility under which the 105 air carrier IFR NMACs occurred is listed in Table 3-1.

TABLE 3-1
VISIBILITY CONDITIONS

| VISIBILITY | FREQUENCY |
|---|---|
| Less than 5 mi | 14 (6 less than 1 mi) |
| Greater than 5 mi | 86 (40 unlimited) |
| Unknown | 5 |
| Total | 105 |

High visibility dominated--a fact that is well known. To obtain a rough estimate of the relevance of Instrument Meteorological Conditions (IMC) to NMACs, we observe that 14 incidents were reported to have occurred with visibility less than 5 miles, while 86 had visibility greater than 5 miles. IMC is usually declared for visibility less than 3 miles (5 miles above 10,000 ft MSL), but these thresholds are not broken out in the NMAC reports. One can then say that less than 1/6 of the NMACs were in IMC.

Of greater interest is the fact that 70 percent of these encounters occurred in bright daylight, and that of these, 93 percent were first sighted when they were less than 1/2 mile away. From this one can infer that if TCAS could provide an aid to visual acquisition, such an aid could be highly valuable. Section 6 will provide a quantitative background for estimating the value of such a feature, and Section 7 will combine all the factors into the fault tree.

### 3.1.3 Operator of Other Aircraft

The other aircraft in the NMAC data were classified as to their type of operator: 9 percent air carrier, 12 percent military, 71 percent general aviation, and 8 percent "other" or unknown.

### 3.1.4 Fraction of Transponder Equipage

The NMAC data base for the years 1973-1980 does not provide a direct answer to the question of transponder equipage of general aviation aircraft, which is of great importance to the collision avoidance system (as well as to ATC automation). However, the new format introduced in 1981 includes this information, so the data for the years 1981-1982 will be used here, both "critical" and "potential" NMAC data in order to augment the sample size. There were 146 of these incidents in which at least one of the aircraft was an air carrier on an IFR flight plan. Although these reports designate whether an aircraft is transponder equipped, they say nothing about Mode C. However, one can look at the type of aircraft encountered when the NMAC occurred and draw some inferences about the level of Mode C equipage. Of 146 incidents, 75 percent were against general aviation aircraft.

Using the 1981-1982 NMAC data, the type of GA aircraft involved in an encounter with an air carrier IFR aircraft was obtained, as well as whether the GA aircraft carried a transponder. Table 3-2 shows this information. It is seen that 90 percent of the GA aircraft involved in these incidents carried transponders.

As both a reasonableness check of this data and as a way to estimate Mode C equipage, the 1981 General Aviation avionics survey (Reference 5) was consulted. Table 3-3 presents the pertinent data. The levels of transponder equipage for all but

TABLE 3-2
NMAC INCIDENTS WITH GA AIRCRAFT (1981, 1982)

| AIRCRAFT TYPE | PERCENT OF NMAC WITH GA AIRCRAFT THIS TYPE | TRANSPONDER EQUIPPED (PERCENT OF TYPE) |
|---|---|---|
| Single Engine, Piston | | |
| 1-3 seats | 14 | 63 |
| 4+ seats | 47 | 90 |
| Twin Engine, Piston | | |
| 1-6 seats | 13 | 100 |
| 7+ seats | 8 | 100 |
| Turboprop | 18 | 100 |
| TOTAL | 100 | 90 |

TABLE 3-3
GENERAL AVIATION EQUIPAGE FOR 1981

| AIRCRAFT TYPE | MODE C (PERCENT OF TYPE) | TRANSPONDER EQUIPPED (PERCENT OF TYPE) |
|---|---|---|
| Single Engine, Piston | | |
| 1-3 seats | 3 | 24 |
| 4+ seats | 34 | 83 |
| Twin Engine, Piston | | |
| 1-6 seats | 82 | 97 |
| 7+ seats | 82 | 90 |
| Turboprop | 92 | 96 |

the smallest class of aircraft compare favorably with those given in Table 3-2. That is, the transponder equipage of those aircraft conflicting with an air carrier is close to that of the national GA fleet. The exception involving small single engine aircraft may indicate that many of the unequipped, small aircraft do not become involved in NMACs with air carrier IFR aircraft.

We will assume that the Mode C percentages in the GA fleet (Table 3-3) apply to the GA aircraft involved in the NMACs. By combining the equipage of all the types based upon the percentage of each involved (even for the small aircraft), it was determined that of the 90 percent of transponder equipped general aviation aircraft involved in the NMACs, 56 percent of these are Mode C equipped. Furthermore, assuming that all air carrier and military aircraft are Mode C equipped, and assuming that "other" aircraft involved are no better equipped than general aviation aircraft, then an overall equipage level can be estimated. The result is that 92 percent of all aircraft involved in the NMACs are estimated to be transponder equipped, 66 percent of which are also Mode C equipped.

As a further check on these numbers, the data obtained by measurement of the airborne traffic environment in the Los Angeles basin was consulted (Reference 6). In that case, 85 percent of the aircraft were found to be transponder equipped, 68 percent of which were Mode C.

Also, the airborne traffic observed over a 5 hour period by the Mode S sensor near Philadelphia (Clementon) showed that 76 percent of the transponders were Mode C. This data sample was taken under good visibility conditions when a substantial amount of uncontrolled traffic was present.

All of the above gives general substantiation of the figures obtained from the NMACs and GA avionics statistics -- 92 percent transponder equipage, 66 percent of which are also Mode C (i.e., 61 percent of aircraft had Mode C transponders).

### 3.1.5 Risk

Figure 3-2 shows the frequency of reported NMACs occurring for each year from 1973 to 1980. The bottom of each bar indicates those NMACs involving at least one air carrier aircraft. Recent experience shows that about 22 air carrier aircraft are involved in an NMAC each year (for air carriers operating on an IFR flight plan, this figure is about 19).

Reference 4 shows that air carriers fly approximately $8 \times 10^6$ hours per year, for 1979 and 1980. Thus, this data indicates that the risk of an air carrier aircraft encountering an NMAC is about $2.8 \times 10^{-6}$ per hour of flight. (Reference 4 also indicates that an average flight is slightly more than one hour. So the risk per flight is roughly equal to the risk per hour.)

For various reasons, some incidents will not be reported. On the other hand some of the encounters may have minimum separations larger than 100 feet -- there is no precise way of measuring the distance. Also, some few air carrier operations are not conducted on IFR flight plan. Since our major interest is for air carrier IFR operations, these factors place an uncertainty on the true risk. A check of this value will be made in later sections using other data. However, as noted earlier, the exact level of risk, while of interest, is not a key parameter in this study since we intend to evaluate directly the relative Risk Ratio.

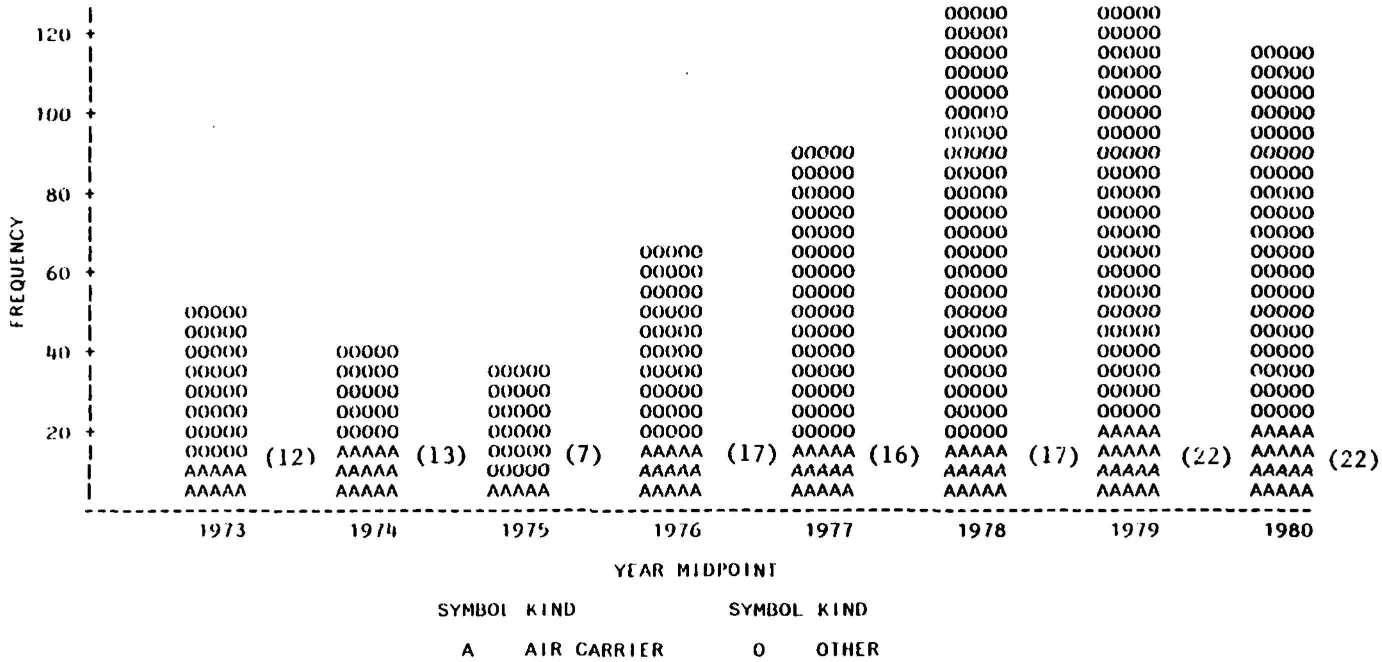



**FIGURE 3-2**
**REPORTED NEAR MIDAIR COLLISIONS**

## 3.2 TCAS Data from Piedmont Flights

Data collected on the on-board TCAS recording system while the equipment was carried on normal Piedmont operational flights provides another source which can be used to further characterize the environment. Of course, this data was for an air carrier flying under IFR all the time. While these routes did not cover all possible cases -- for example, Piedmont did not fly transcontinental, nor did they land at small commuter airports -- they were typical (see Reference 8).

In order to conserve recording resources, the TCAS recording system was automatically turned on only when TCAS activity occurred. This was accomplished by starting the recording whenever the Traffic Advisory criteria were met, and stopping the recording 10 seconds after the Traffic Advisory was removed. Accordingly, the Piedmont data is present only when a TA or RA is posted. Two distinct methods of data reduction were used: the first analyzed only the inciting tracks -- those tracks which caused the TA or RA --; the second analyzed all tracks that were in the track file during the time that the recorder was energized.

### 3.2.1 Inciting Tracks

Whenever a TA or RA was posted, its track was examined for the duration of the encounter, and various inferences were drawn from this data (Reference 9). The key items obtained from this investigation were:

- The altitude distribution of the RAs

- The relative altitude distribution at the closest point of approach

- The predicted altitude crossings when the TCAS aircraft was level

- An estimate of the risk of encountering an NMAC

### 3.2.1.1 Altitude Distribution

Considering the sample size, the distribution in altitude of the RAs is roughly similar to that of the NMACs previously reported; 57 percent occurred below 10,000 ft and one occurred as high as 30,000 ft.

### 3.2.1.2 Relative Altitude Distribution

If the tracks causing the RA are followed through until the closest point of approach, and at that point the relative altitude separation is noted, the data in Figure 3-3 is obtained. While the sample size is relatively small, (21 points), this distribution appears to be fairly uniform to about 1400 ft, at which point it tapers off. To inquire further into the distribution, the TAs were examined, these are shown in Figure 3-4. Here, the sample size is larger (140 points). Two characteristics of this data are notable: first, the distribution below 700 feet, or so, is, indeed, relatively uniform; and second, there is a pronounced peak at 1000 ft. However, the peak in the TAs is caused by the normal IFR separation, 1000 ft; the TA vertical threshold, provided other conditions are satisfied, is 1200 feet.

The approximately uniform distribution could arise because aircraft actually are flying random altitudes (not too likely, given the ATC system; and contradicted by the existence of the peak in TAs at 1000 ft), or it could arise because frequent altitude transitions occur. To test this hypothesis, an

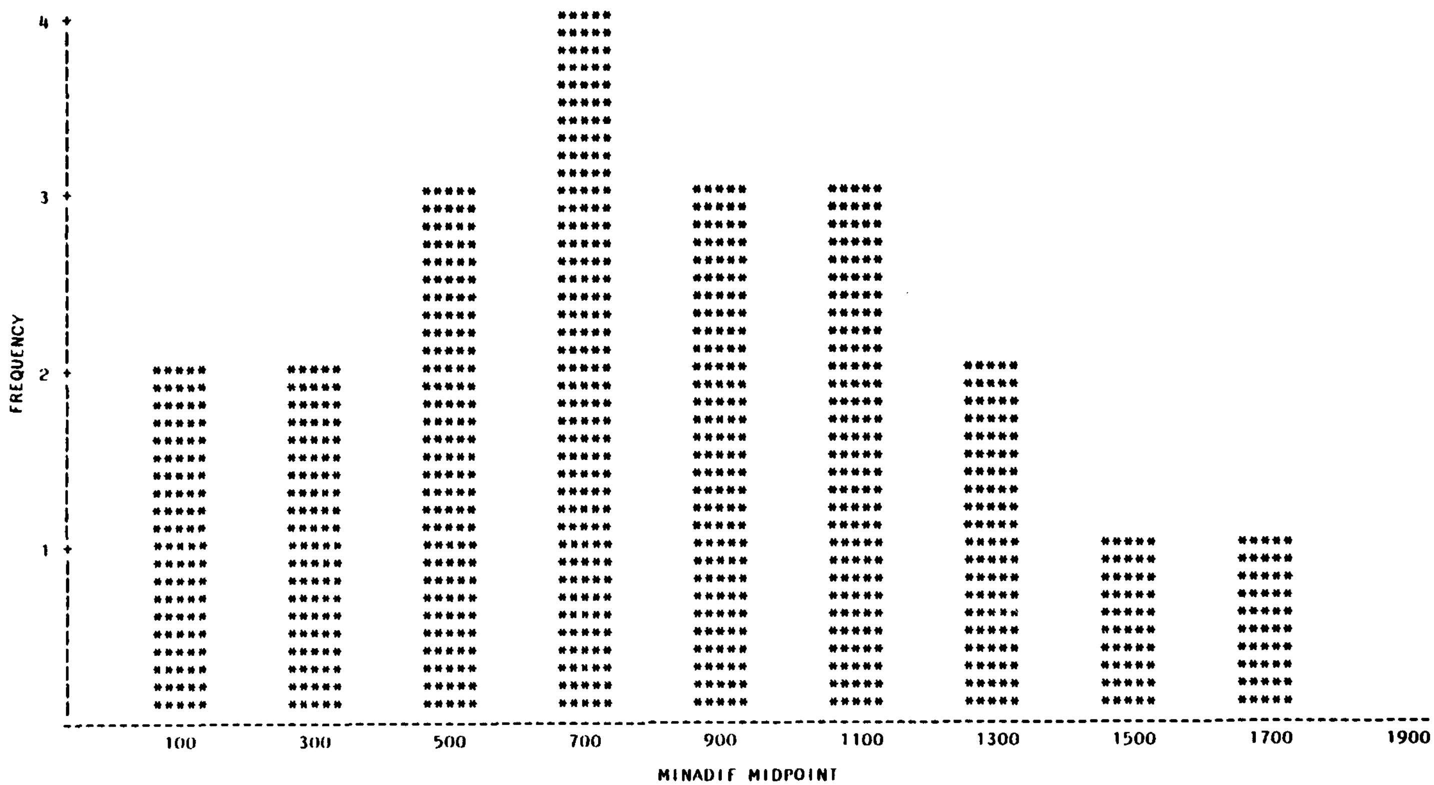



**FIGURE 3-3**
**RELATIVE ALTITUDE DISTRIBUTION OF RAs**

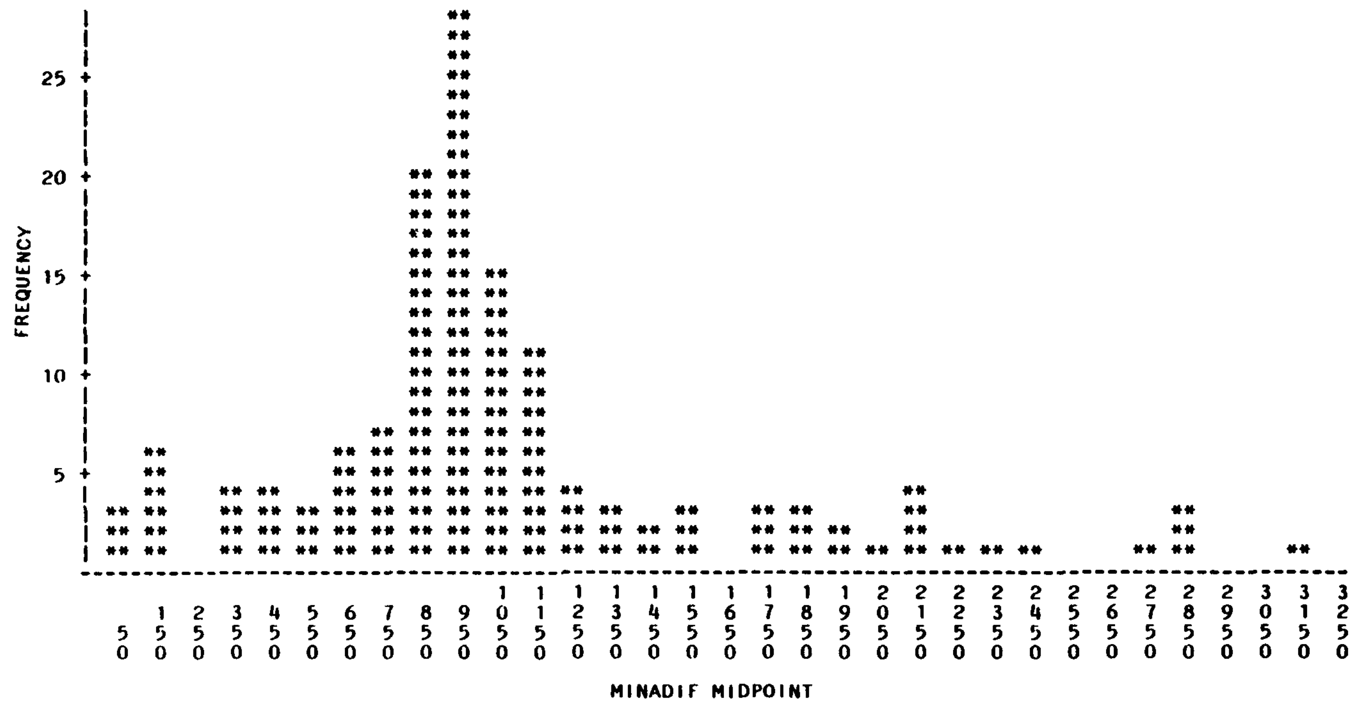



**FIGURE 3-4**
**RELATIVE ALTITUDE DISTRIBUTION OF TAs**

examination was made of the vertical rates at the time of the TA. This is shown in Table 3-4, where it is seen that in only 25 percent of the encounters did both aircraft have a vertical rate of less than 300 fpm. The result of vertical rates for either aircraft is to spread out the relative altitudes at the closest point of approach, as observed. The uniform distribution phenomenon is an important result which will be used in subsequent analysis.

Finally, it was noted that in only one instance (4.8 percent of all RAs) was the vertical separation less than 100 ft.

#### 3.2.1.3 Predicted Altitude Crossings for Level TCAS

The fraction of RAs for which the TCAS aircraft is level, and an altitude crossing is predicted before the closest point of approach, is an important factor in the environment, as will be discussed in Section 4.2. Since the number of RAs was small, we examined the TAs for which such a crossing was predicted.

It was observed that when the TCAS aircraft was level, 14 percent of all intruders were predicted to cross in altitude between the posting of the Traffic Advisory and the closest point of approach.

#### 3.2.1.4 Risk

No NMACs were encountered during the 950 flight hours of the Piedmont trials. However, RAs of some type did occur about once every 40 hours. An estimate of the risk of encountering an NMAC will be made using this alarm rate together with an estimate of how often enountering aircraft might come within 100 ft vertically and 500 ft horizontally.

TABLE 3-4
VERTICAL RATE CHARACTERISTICS

| TCAS | INTRUDER | | TOTAL |
|---|---|---|---|
| | < 300 fpm | ≥ 300 fpm | |
| < 300 fpm | .25 | .22 | .47 |
| ≥ 300 fpm | .31 | .22 | .53 |
| TOTAL | .56 | .44 | 1.00 |

In Section 3.2.1.2 it was noted that 4.8 percent of the RAs passed within 100 ft vertically at the closest point of approach. In Appendix B, an estimate is made of the probability that the two aircraft will come within 500 ft horizontally of each other, given that an RA has occurred. This estimate assumes a uniform distribution of headings, and it makes use of the recorded maximum closing velocity, which can be obtained from the data. On an overall basis the estimate of the probability of coming within 500 ft horizontally, given that an RA is being generated, is .028. Assuming that the horizontal and vertical proximity probabilities are independent, the resulting risk of an NMAC is $1/40 \times .048 \times .028 = 3.4 \times 10^{-5}$ per hour. Section 3.1.5 also obtained an estimate of this risk. After one more estimate is obtained, all three will be combined.

### 3.2.2 All Tracks

In addition to the track causing the TA or RA, the recorder maintains records of all tracks in view. This enables one to develop a significantly larger data base than the 140 TAs. It does, however, require a large amount of time and computer resources to interpret and utilize this data. A sampling approach was taken whereby an 80-second window was opened when the recorder started. Only one window was permitted for each TA. A new TA -- occurring minutes, hours, or days later -- opened a new window of data for analysis. Each track in the window was sampled 5 times across its extent. (Many tracks lasted for a much shorter time than the 80-second window; none were used if they lasted less than 16 seconds.) The tracks were then classified as being "level" (less than 480 fpm vertical rate), "constant rate", or "accelerating" (any change of 480 fpm or more). The characteristics that are needed will be shown later in Section 4.2. It was noted, however, that the fraction of level tracks and the fraction of those that are projected to cross in altitude are comparable with those of the inciting tracks just discussed in Section 3.2.1.3.

### 3.3 TCAS Data From FAA Flights

Data collected from previous TCAS flight tests utilizing FAA Technical Center aircraft were analyzed to determine the following characteristics of the traffic environment:

- Distribution of horizontal and vertical separation at Closest Point of Approach (CPA)
- Distribution of vertical rate estimates
- Frequency and type of vertical profile changes
- Probability of an NMAC

The data base for this analysis is ten flight tests conducted between 19 August and 28 October, 1981. Air Traffic Control Radar Beacon System (ATCRBS) surveillance messages were recorded by the Dalmo Victor on-board flight recording system. Unlike the Piedmont flights, this TCAS data recording was continuous, with all tracks associated with targets within TCAS surveillance being analyzed. There were 316,777 ATCRBS surveillance messages and 7,748 unique ATCRBS tracks. Of these, 555 were tracks of aircraft on the ground. The majority of these ground tracks would not have caused alarm actions because of radar altimeter filtering of threats on the ground (not implemented at the time of the flights, however), so they were manually removed from the data base. To facilitate analysis, a subset of the data base was created which was composed of all tracks with at least 10 good Mode C reports. The total data base included 92,261 TCAS cycles, equivalent to 25.6 hours of flight data. This flight data contained 88 track hours of data suitable for analysis. Table 3-5 presents the statistics associated with each test flight.

The majority of the flights were conducted at the FAA Technical Center. These flight tests were performed to evaluate the command resolution logic of the Dalmo Victor TCAS System. A TCAS equipped aircraft and an unequipped aircraft (altitude reporting transponder only) were used in these flight tests.

The intruder aircraft could perform as either an ATCRBS intruder or a Mode S intruder. (The October 16 flight test was performed primarily to evaluate the TCAS resolution logic between two TCAS equipped aircraft.) Two test flights were performed in high density airspace. Low approaches were flown at Chicago O'Hare Airport, and 14 planned encounters were flown in the Washington, D.C. area. Thirteen additional encounters would have been observed at Chicago, if the "radar altimeter filter" had not been applied. For all ten flights, 153 resolution encounters occurred, using the TCAS logic of April 1982. Of the 153 resolution encounters, almost all were preplanned. The only encounters of opportunity were five in Chicago, five in Washington, D.C., and eight which occurred on the numerous flights in the Atlantic City area.

The duration of tracks declared suitable for analysis was obtained. The average duration was approximately 100 seconds. Figure 3-5 presents the distribution of track durations. (Note the abscissa does not have a constant scale.)

TABLE 3-5
FLIGHT TEST DATA BASE

| FLIGHT TEST DATES | FLIGHTS TEST LOCATION | RESOLUTION ENCOUNTERS | NUMBER OF SURVEILLANCE MESSAGES | NUMBER ATCRBS TRACKS | ATCRBS GROUND TRACKS | NUMBER OF TRACKS* | NUMBER CYCLES (SECONDS) |
|---|---|---|---|---|---|---|---|
| 8/19/81 | Tech. Ctr. | 11 | 15415 | 678 | 44 | 185 | 7979 |
| 9/11/81 | Tech. Ctr. | 9 | 36425 | 546 | 45 | 273 | 5926 |
| 9/17/81 | Tech. Ctr. | 7 | 19018 | 343 | 17 | 149 | 5621 |
| 9/23/81 | Tech. Ctr. | 19** | 38746 | 478 | 20 | 243 | 9737 |
| 9/24/81 | Tech. Ctr. | 22** | 15545 | 231 | 49 | 112 | 6355 |
| 9/28/81 | Washington | 19** | 52060 | 1834 | 272 | 552 | 11528 |
| 9/30/81 | CHI O'Hare | 5 | 43503 | 2267 | 26 | 520 | 13251 |
| 10/16/81A | Tech. Ctr. | 22** | 32797 | 516 | 25 | 298 | 10559 |
| 10/16/81B | Tech. Ctr. | 25** | 34051 | 520 | 33 | 261 | 10998 |
| 10/28/81 | Tech. Ctr. | 14** | 29208 | 335 | 24 | 188 | 10307 |
| TOTAL VALUES | | 153 | 316777 | 7748 | 555 | 2781 | 92261 (25.6 hrs) |

* With a minimum of 10 good altitude reports.

** Includes Mode S encounters.

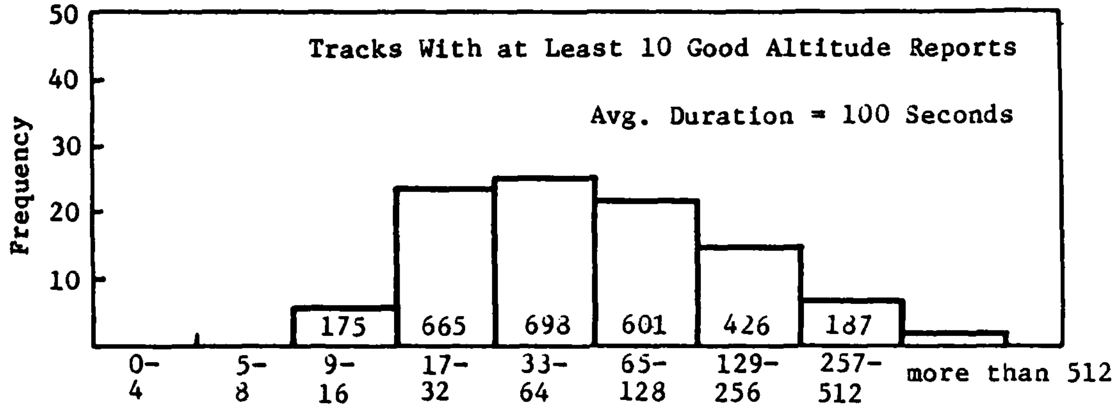
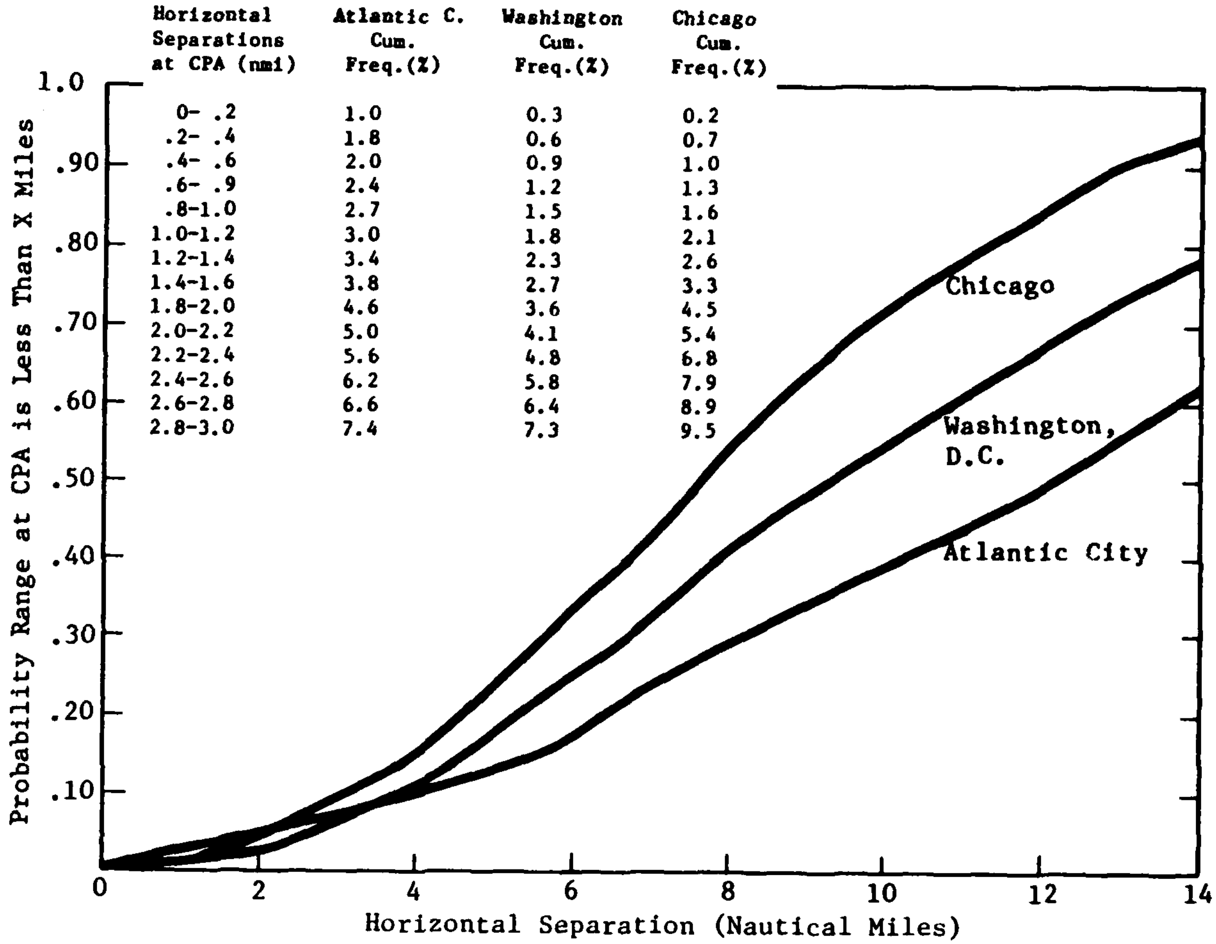



**FIGURE 3-5**
**HISTOGRAMS OF ATCRBS SURVEILLANCE TRACK DURATIONS**

After identifying the tracks which were suitable for analysis, a technique was developed to obtain accurate vertical position and vertical rate estimates based on the entire track history. A seven point moving polynomial fit was used to provide smoothed position and rate estimates from the Mode C report history. This technique provided considerably more accurate information than could have been obtained using the results of the predictive altitude tracker in the TCAS surveillance system. The polynomial fit technique takes advantage of all subsequent reports associated with each track. Since the range information is not quantized as coarsely as the altitude, data from the TCAS range tracker is more accurate and was used without additional smoothing.

### 3.3.1 Distribution of CPA Conditions and Aircraft Density Impact

Figure 3-6 presents the cumulative distributions for the horizontal separations at the closest point of approach (CPA) for each of the three test locations. Up to a range of 2.6 nautical miles, little difference in the distributions can be detected. Beyond this range, however, the density effects become apparent. The probability of horizontal separation being less than 6 nautical miles in Chicago is more than twice the probability in the Atlantic City area. The lack of a density effect on the distributions for ranges less than 2.6 nautical miles reflects the influence of the Air Traffic Control System. Figure 3-6 can be used to assign probabilities to hypothesized encounter range conditions for the System Safety study.



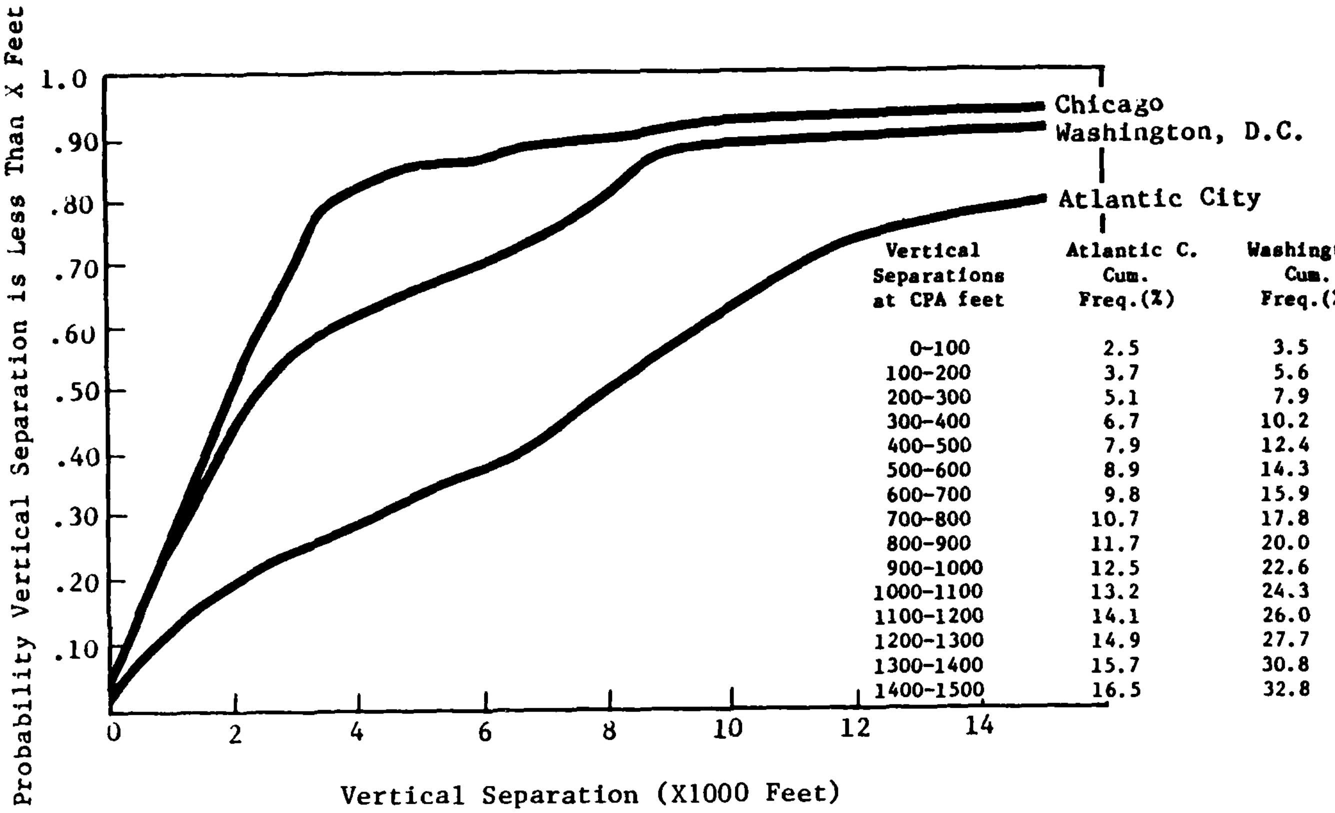

| Horizontal Separations at CPA (nmi) | Atlantic C. Cum. Freq.(%) | Washington Cum. Freq.(%) | Chicago Cum. Freq.(%) |
|---|---|---|---|
| 0- .2 | 1.0 | 0.3 | 0.2 |
| .2- .4 | 1.8 | 0.6 | 0.7 |
| .4- .6 | 2.0 | 0.9 | 1.0 |
| .6- .9 | 2.4 | 1.2 | 1.3 |
| .8-1.0 | 2.7 | 1.5 | 1.6 |
| 1.0-1.2 | 3.0 | 1.8 | 2.1 |
| 1.2-1.4 | 3.4 | 2.3 | 2.6 |
| 1.4-1.6 | 3.8 | 2.7 | 3.3 |
| 1.8-2.0 | 4.6 | 3.6 | 4.5 |
| 2.0-2.2 | 5.0 | 4.1 | 5.4 |
| 2.2-2.4 | 5.6 | 4.8 | 6.8 |
| 2.4-2.6 | 6.2 | 5.8 | 7.9 |
| 2.6-2.8 | 6.6 | 6.4 | 8.9 |
| 2.8-3.0 | 7.4 | 7.3 | 9.5 |

**FIGURE 3-6**
**DISTRIBUTION OF HORIZONTAL SEPARATION AT CPA**

In Figure 3-7, the cumulative probabilities of the vertical separation at CPA are shown. Several points should be noted. The density effect is apparent for all vertical separations. The probability of an aircraft passing within 500 feet vertically at CPA is almost twice as high in Chicago and Washington, D.C., as it was at the FAA Technical Center. An interesting point to be made is the comparison of the cumulative probabilities at 1200 feet, the vertical threshold for proximity advisories. More than 1/3 of all tracks in the Chicago area satisfy this condition compared to less than 15 percent of tracks in the Atlantic City area.

All three distributions shown are almost uniform up to about 900 feet vertical separation; the uniformity continues beyond 1400 feet for the more dense environments in Washington, D.C., and Chicago. The results of a chi-squared goodness-of-fit test (5 percent level of significance) on the Chicago and Washington distribution between zero and 1000 ft, support the hypothesis of a uniform distribution. It was not meaningful to perform a similar analysis on the data at the FAA Technical Center because of the high incidence of planned encounters there. The results of this analysis are consistent with those presented previously in Section 3.2. The analysis of vertical and horizontal CPA conditions indicates that, as the density increases, the vertical separation distribution at CPA is affected more than the horizontal separation distribution.

The assumption of independence of horizontal and vertical separation components at CPA is strongly supported by statistical tests. The correlation coefficient is .0177 for the nonparametric Spearman rank-order statistic where 0 implies




| Vertical Separations at CPA feet | Atlantic C. Cum. Freq.(%) | Washington Cum. Freq.(%) | Chicago Cum. Freq.(%) |
|---|---|---|---|
| 0-100 | 2.5 | 3.5 | 3.1 |
| 100-200 | 3.7 | 5.6 | 5.2 |
| 200-300 | 5.1 | 7.9 | 7.9 |
| 300-400 | 6.7 | 10.2 | 10.2 |
| 400-500 | 7.9 | 12.4 | 12.3 |
| 500-600 | 8.9 | 14.3 | 14.4 |
| 600-700 | 9.8 | 15.9 | 17.3 |
| 700-800 | 10.7 | 17.8 | 19.9 |
| 800-900 | 11.7 | 20.0 | 22.7 |
| 900-1000 | 12.5 | 22.6 | 26.5 |
| 1000-1100 | 13.2 | 24.3 | 30.0 |
| 1100-1200 | 14.1 | 26.0 | 32.5 |
| 1200-1300 | 14.9 | 27.7 | 34.9 |
| 1300-1400 | 15.7 | 30.8 | 37.2 |
| 1400-1500 | 16.5 | 32.8 | 39.2 |

**FIGURE 3-7**
**DISTRIBUTION OF VERTICAL SEPARATION AT CPA**

no correlation, +1 implies perfect positive correlation, and -1 implies perfect negative correlation. Several other tests were made with equally strong rejection of dependence.

Secondary encounters as a result of aircraft responding to TCAS RAs have not been observed on the Technical Center Test Flights (25 hrs) or in simulations of TCAS in terminal environments (44 hrs) at the ATC simulation facility in Atlantic City. Simulation of 2D logic at both Chicago (Reference 11) and Knoxville (Reference 12) and simulation of vertical logic at Knoxville (Reference 13) under IFR and VFR conditions resulted in no secondary encounters.

### 3.3.2 Vertical Rates

The final information obtained on the entire track data base was the distribution of vertical rates. The rate estimates were obtained on a per scan basis and represent the time distribution of vertical rates. Table 3-6 presents the vertical rate distributions for each flight. A fairly consistent 60 percent of the vertical rate estimates reflect level or nearly level (0-300 fpm) aircraft. (This compares favorably with the 56 percent noted previously from the Piedmont data in Table 3-4.) About 22 percent of the rate estimates fell in the 600 to 1500 feet per minute range. The highest observed climb rate was 4200 feet per minute. Descent rates in excess of 6000 feet per minute were only observed during planned encounter scenarios. The highest descent rate not associated with a planned scenario was 2900 feet per minute.

### 3.3.3 Vertical Profile Changes

An important question is the probability of change in the vertical profile of aircraft being tracked by TCAS. Using the previously discussed polynomial fit of data, a method of detecting changes in the vertical profile was developed. A

TABLE 3-6
FLIGHT TEST SURVEILLANCE VERTICAL RATES (PER SCAN BASIS)

| ABSOLUTE VERTICAL RATE (Ft/Min) | 8/19/81 ABS. FREQ. | 8/19/81 REL. FREQ. | 9/11/81 ABS. FREQ. | 9/11/81 REL. FREQ. | 9/17/81 ABS. FREQ. | 9/17/81 REL. FREQ. | 9/23/81 ABS. FREQ. | 9/23/81 REL. FREQ. | 9/24/81 ABS. FREQ. | 9/24/81 REL. FREQ. | 9/28/81 ABS. FREQ. | 9/28/81 REL. FREQ. | 9/30/81 ABS. FREQ. | 9/30/81 REL. FREQ. | 10/16/81A ABS. FREQ. | 10/16/81A REL. FREQ. | 10/16/81B ABS. FREQ. | 10/16/81B REL. FREQ. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LEVEL | 3681 | (28%) | 7957 | (25%) | 4303 | (28%) | 9351 | (27%) | 2551 | (21%) | 8672 | (20%) | 10265 | (27%) | 7574 | (28%) | 8035 | (29%) |
| 0-300 | 5024 | (38%) | 11280 | (36%) | 4688 | (30%) | 11258 | (33%) | 3951 | (33%) | 11561 | (27%) | 8678 | (23%) | 8688 | (32%) | 8352 | (30%) |
| 300-600 | 1855 | (14%) | 4134 | (13%) | 2243 | (15%) | 4169 | (12%) | 1275 | (11%) | 5519 | (15%) | 5066 | (13%) | 3148 | (12%) | 3216 | (12%) |
| 600-900 | 1388 | (10%) | 3416 | (11%) | 1748 | (11%) | 3459 | (10%) | 1122 | (9%) | 5376 | (13%) | 4613 | (12%) | 2353 | (9%) | 2361 | (9%) |
| 900-1200 | 527 | (4%) | 1529 | (5%) | 1045 | (7%) | 2027 | (6%) | 871 | (7%) | 3097 | (7%) | 3493 | (9%) | 1581 | (6%) | 1722 | (6%) |
| 1200-1500 | 297 | (2%) | 1198 | (4%) | 671 | (4%) | 1365 | (4%) | 687 | (6%) | 2346 | (6%) | 2185 | (6%) | 1279 | (5%) | 1429 | (5%) |
| 1500-1800 | 173 | (1%) | 872 | (3%) | 216 | (1%) | 1073 | (3%) | 419 | (3%) | 1574 | (4%) | 1356 | (4%) | 657 | (2%) | 821 | (3%) |
| 1800-2100 | 106 | (1%) | 483 | (2%) | 155 | (1%) | 634 | (2%) | 320 | (3%) | 981 | (2%) | 806 | (2%) | 565 | (2%) | 613 | (2%) |
| 2100-2400 | 84 | (1%) | 275 | (1%) | 185 | (1%) | 481 | (1%) | 274 | (2%) | 674 | (2%) | 614 | (2%) | 402 | (1%) | 397 | (1%) |
| 2400-2700 | 51 | (0%) | 96 | (0%) | 90 | (1%) | 268 | (1%) | 211 | (2%) | 547 | (1%) | 529 | (1%) | 250 | (1%) | 283 | (1%) |
| 2700-3000 | 58 | (0%) | 45 | (0%) | 23 | (0%) | 184 | (1%) | 153 | (1%) | 391 | (1%) | 285 | (1%) | 114 | (0%) | 227 | (1%) |
| 3000-4000 | 132 | (1%) | 167 | (1%) | 68 | (0%) | 196 | (1%) | 152 | (1%) | 411 | (1%) | 378 | (1%) | 151 | (1%) | 96 | (0%) |
| 4000-6000 | 21 | (0%) | 106 | (0%) | 24 | (0%) | 30 | (0%) | 33 | (0%) | 111 | (0%) | 68 | (0%) | 79 | (0%) | 113 | (0%) |
| 6000 | 0 | (0%) | 20 | (0%) | 0 | (0%) | 0 | (0%) | 0 | (0%) | 43 | (0%) | 0 | (0%) | 16 | (0%) | 31 | (0%) |

track or portion of a track was declared level when the maximum vertical displacement in the tracked position did not exceed 150 feet. A change in vertical profile was declared when the variation in the error of the polynomial fit exceeded a specified threshold.

Once a profile was declared, the track was split into track segments by the profile change. The three vertical profiles are climb, level, and descend. Profile changes are classified in Table 3-7 into one of four subpopulations; level to climb, level to descend, climb to level, and descend to level. If a track exhibited no profile change, it was classed as either level, climbing, or descending.

Over 65 percent of the tracks exhibited no profile changes. The remaining tracks exhibited one or more profile changes. If a track exhibited a climb and then a descend, two profile changes were declared; climb to level, and level to descend. A sequence seen on the Chicago tape was a descent to about 2400 ft MSL, followed by a level segment and then followed by another descend segment. This represents ATC control procedures for aircraft being vectored to the ILS final approach course at Chicago, O'Hare. Almost twice as many profile changes involving a descent portion occurred as compared with profile changes involving a climb. This again, is a characteristic of the ATC environment in the terminal area. Only 6 percent of the tracks exhibited more than one profile change.

Even after the tracks are divided into segments by the profile changes, the average track segment duration remained high. The duration of level segments was 60.2 seconds, 46.9 seconds for

TABLE 3-7
DISTRIBUTION OF VERTICAL PROFILE CHARACTERISTICS
(ALL TRACKS BELOW 10,000 FEET MSL)

| | FREQUENCY | PERCENT |
|---|---|---|
| CLIMB | 193 | 11.7 |
| LEVEL | 618 | 37.3 |
| DESCEND | 302 | 18.2 |
| CLIMB TO LEVEL | 102 | 6.2 |
| DESCEND TO LEVEL | 183 | 11.1 |
| LEVEL TO CLIMB | 92 | 5.6 |
| LEVEL TO DESCEND | 164 | 9.9 |
| | 1654 | 100.0 |

descend segments and 50.2 seconds for climb segments. The minimum length segment was 11 seconds and the maximum length was 484 seconds.

Of primary importance is the probability of profile changes occuring within the time period the intruder may be selected for threat resolution (approximately 40 seconds). Figures 3-8 and 3-9 present the probability of a profile change for a given track length. To obtain the probability of a profile change during a 10 second period, every track was divided into 10-second increments and the number of increments containing a profile change was tallied. The procedure was repeated for 20 seconds, and so forth. Figure 3-8 indicates approximately one track in 12 above 10,000 feet MSL would include a profile change during a 40 second period. Similarly, about one track in eight below 10,000 feet would contain a profile change during a 40 second period.

Use of the preceding information for determining probability at any instant in time of a potential vertical fake-out maneuver is shown in Appendix C.

Examination of TCAS surveillance data indicates that the probability of a profile change relative to the TCAS aircraft is more dependent upon the flight environment than upon proximity to the TCAS aircraft. For the Chicago and Atlantic City test flights, the probability of a profile change of a tracked aircraft can be considered uniform in both range and altitude. The dashed lines in Figures 3-10 and 3-11 are a normalized probability which attempts to factor out the increased areas of coverage, and therefore increasing number of tracks, as range increases. The significant point discovered

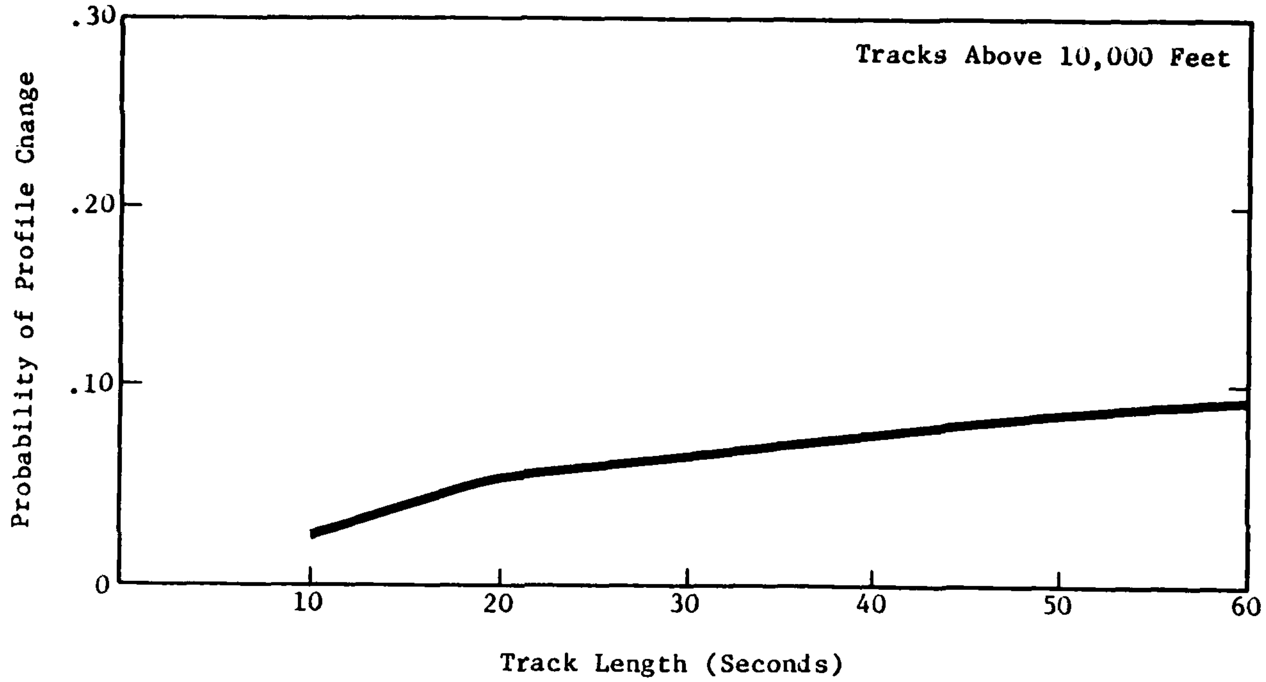



**FIGURE 3-8**
**PROBABILITY OF HIGH ALTITUDE PROFILE CHANGE WITH TRACK LENGTH**

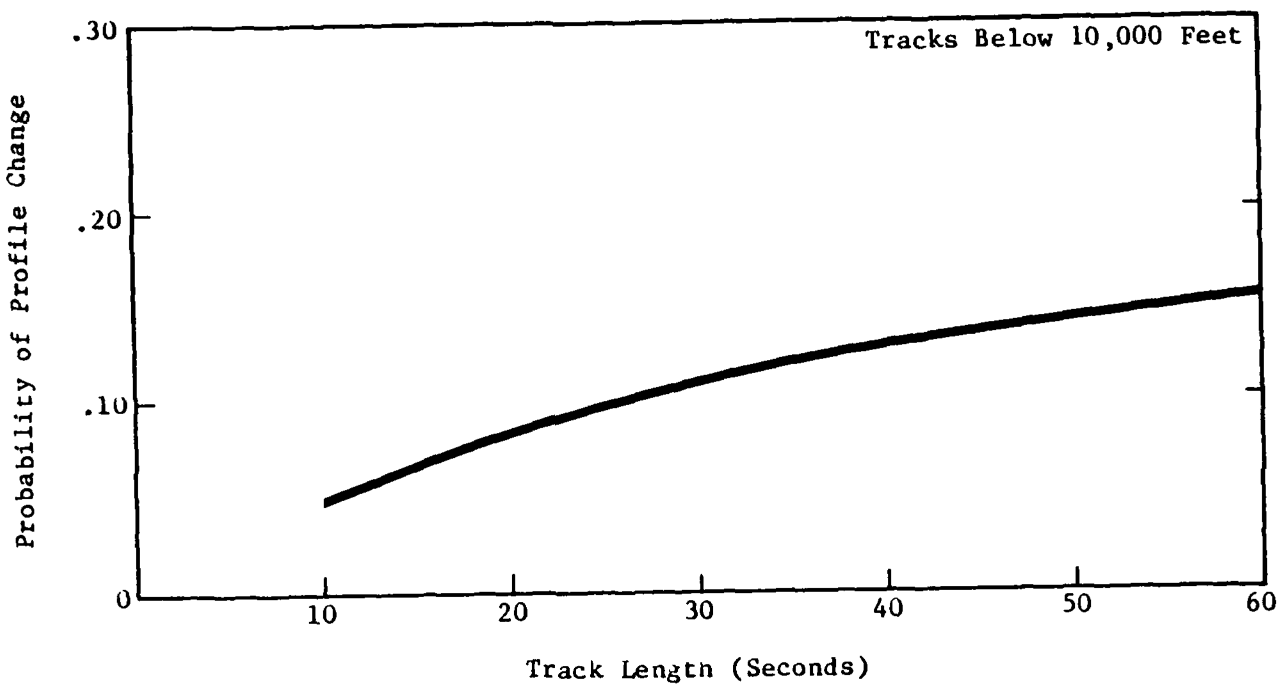



**FIGURE 3-9**
**PROBABILITY OF LOW ALTITUDE PROFILE CHANGE WITH TRACK LENGTH**

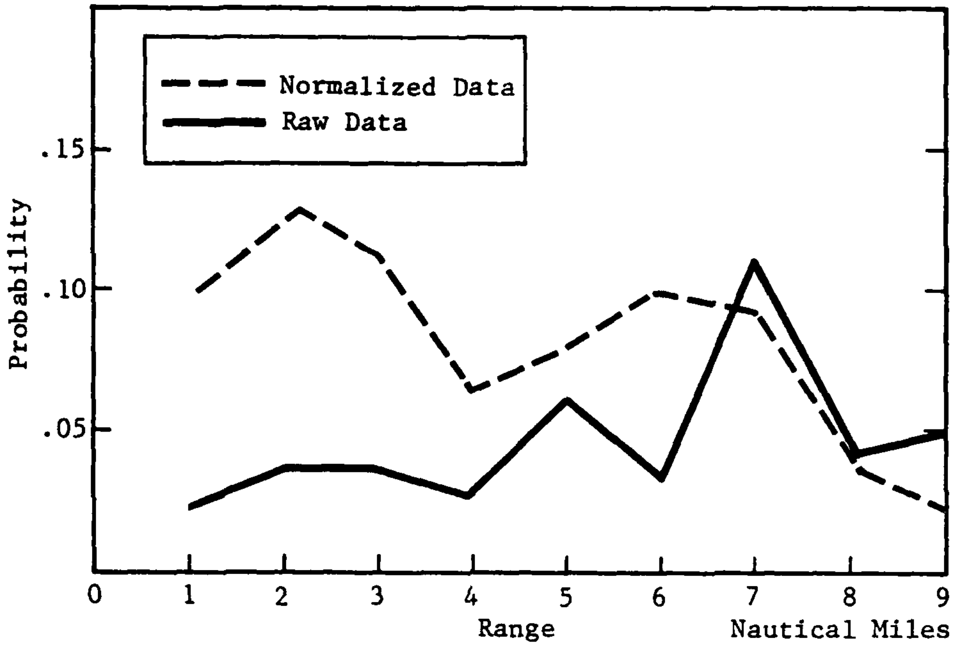



**FIGURE 3-10**
**PROBABILITY OF A PROFILE CHANGE WITH RANGE FROM TCAS AIRCRAFT (CHICAGO AND ATLANTIC CITY)**

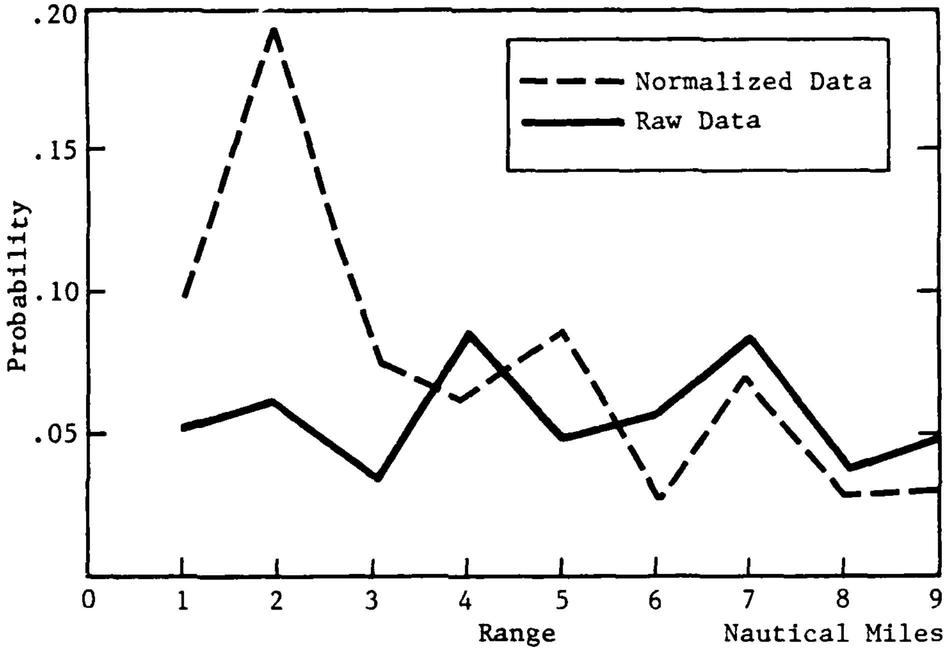



**FIGURE 3-11**
**PROBABILITY OF A PROFILE CHANGE WITH RANGE FROM TCAS AIRCRAFT (WASHINGTON)**

in this approach was the high probability at 2 nmi for a profile change in the Washington environment. This is due to the arrival pattern, stop descents, and operational procedures employed for the crossing runways at Washington. Although the actual distribution of where profile changes occur change with environment, it is reasonable to assume a uniform distribution across both range and altitude for use in the fault tree analysis since this is the most likely situation to be encountered.

The peak accelerations during the profile changes were also reviewed. Acceleration distributions were developed for each of the four profile changes. The distributions are shown in Figure 3-12. The modes of the positive g maneuvers, level to climb, and descend to level, are higher than the modes of the negative g maneuvers. This is expected. Point estimates for critical values for each of the acceleration distributions are shown in Table 3-8.

Results indicate that 3/4 of all accelerations are less than 1/5 g, with average accelerations slightly greater than 1/8 g. The 75th and 90th percentile points are larger for the positive g maneuvers than for the negative g maneuvers. When all accelerations are grouped together, 95 percent of the time the magnitude is less than 12 feet/second$^2$ (0.37g).

### 3.3.4 Estimated Risk of Encountering an NMAC

The uniform altitude distribution can be used to estimate the risk of encountering a critical NMAC, based on the Chicago data, which had no planned encounters. Figure 3-6 gave the probability of a horizontal approach to within 0.2 nmi to be .002. Although not shown on Figure 3-6, the data tabulation shows that probability to be .0005 within 0.1 nmi.

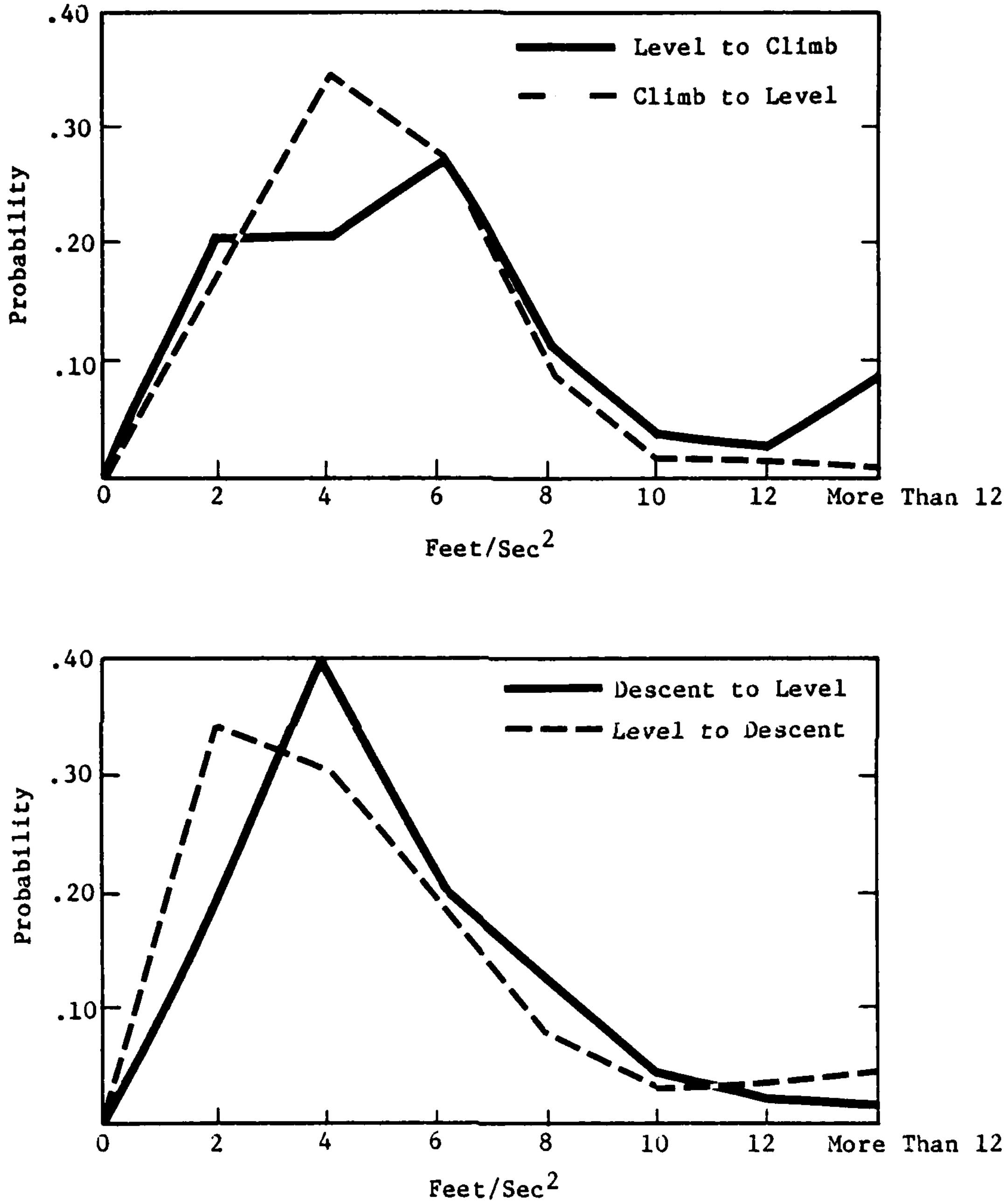



**FIGURE 3-12**
**DISTRIBUTION OF ACCELERATION MAGNITUDES**

TABLE 3-8
ACCELERATION STATISTICS

| TYPE OF ACCELERATION | AVERAGE ($ft/sec^2$) | 75th PERCENTILE ($ft/sec^2$) | 90th PERCENTILE ($ft/sec^2$) |
|---|---|---|---|
| LEVEL TO CLIMB | 5.19 | 8.3 | 11.0 |
| DESCEND TO LEVEL | 4.40 | 6.4 | 8.6 |
| LEVEL TO DESCEND | 4.00 | 5.6 | 8.2 |
| CLIMB TO LEVEL | 4.72 | 6.0 | 8.5 |

Figure 3-7 shows the probability of a vertical separation of 100 ft or less to be .031. Table 3-5 showed the total time in the Chicago area to be 13,251 seconds (3.7 hr). The risk of encountering an NMAC is therefore: $.0005 \times .031 / 3.7 = 4.2 \times 10^{-6}$ per hour.

This compares favorably with the values of $3.4 \times 10^{-5}$ obtained by using Piedmont data, and $2.8 \times 10^{-6}$ obtained from the NMAC reports. Further, the operational experience of United Airlines (Appendix M) is $5.1 \times 10^{-6}$. A value of $1 \times 10^{-5}$ per hour will be used throughout the remainder of this study.

## 4. ANALYSIS OF PRINCIPAL LIMITATIONS TO TCAS

The TCAS system is a cooperative system in that information on the intruder is obtained by interrogating its ATC transponder and then predicting whether the next half-minute or so will bring the aircraft too close. Such a system, as was pointed out earlier, must consider some basic limitations; the probabilities of these are evaluated independently in this section for later inclusion in the fault tree. Other faults, essentially mechanical failures, are evaluated in Section 5. Later, in Section 7, the interaction of all elements of the environment will be explored to arrive at an overall evaluation of risk. The three principal limitations to be evaluated here are: (1) the effect of aircraft without transponders interacting with TCAS, (2) the effect of altimetry errors, and (3) the effect of sudden maneuvers by the intruder.

### 4.1 Intruders Without Mode C Transponders

Section 3.1.4 estimated that 61 percent of the intruders involved in an NMAC would have Mode C altitude reporting. This represents the maximum benefit that the TCAS Resolution Advisory could provide in today's environment. That is, at best, 61 percent of the current NMACs could be avoided with today's level of equipage.

It was noted, however, that a large fraction of the aircraft involved in NMACs have transponders (92 percent), even if they do not have Mode C. If the non-Mode C tracking feature were available in TCAS, "altitude unknown" Traffic Advisories could be provided. If the intruder is really on a near collision course, this feature, patterned after the ATC practice of announcing traffic of concern, should be helpful in alerting the TCAS pilot.

## 4.2 The Effect of Altimetry Errors

The susceptibility of TCAS to error in reported altimetry can be evaluated by analyzing, for "proximate encounters" those combinations of encounter geometry and altimetry error that would produce a resolution advisory which, if followed, would result in less than 100 ft vertical separation. The hazardous situation (NMAC) will then exist if the aircraft are also in close horizontal proximity.

### 4.2.1 Methodology

Some combinations of altimetry error and altitude separation can render TCAS ineffective -- the NMAC will occur regardless. Other combinations exist for which TCAS would degrade separation, actually inducing an NMAC. Therefore, to have an NMAC with TCAS one of two conditions must exist:

1. In the absence of TCAS, an NMAC would have occurred; altimetry error renders TCAS ineffective.

2. In the absence of TCAS, a proximate encounter would have occurred (close horizontally and greater than 100 ft vertically); altimetry error results in TCAS generating an RA that produces an NMAC.

One can take a large enough region of vertical separation, say 1000 ft, determine the number of proximate encounters in terms of the pre-existing NMAC encounters, and then find the fraction of combinations of altimetry error and vertical separation for these encounters that would result in an NMAC. (The value of 1000 ft is large enough to account for the anticipated magnitudes of altimetry error and desired vertical separation.)

In Section 3, the vertical separation of aircraft at their closest point of approach was determined -- it is essentially a uniform distribution. This characteristic behavior was observed both on the Piedmont flights and on the FAA flights. Based on that vertical distribution, we obtain the risk of a proximate encounter by multiplying the number of NMACs by ten (10 times 100 ft equals 1000 ft), as illustrated in Figure 4-1. (There is no change in the horizontal dimension.) Then we can determine what fraction of those encounters would come within 100 ft (an NMAC) because of TCAS altimetry errors. If the error were zero, none would -- if the advisory were followed, the objective separation of ALIM plus some margin would be achieved.

The measure of comparison of the risk of encountering a critical NMAC with TCAS to that without TCAS is called the Risk Ratio. In this case, a non-zero Risk Ratio is caused solely by altimetry error. Later, other factors will be included.

Figure 4-2 shows the geometrical relations, at the time of the start of the RA, that exist for a TCAS encounter in level flight. As sketched, the intruder is projected to pass d ft above the TCAS; however, the reported error, e, makes it appear to TCAS that the apparent separation would be (d+e). If the aircraft have linear vertical rates, the effect is essentially the same as for level flight, except that d is the predicted separation at the closest point of approach.

In ideal operation, with no altimetry error, the TCAS aircraft would descend if d were positive and climb if it were negative. The RA would stay posted until the true separation,

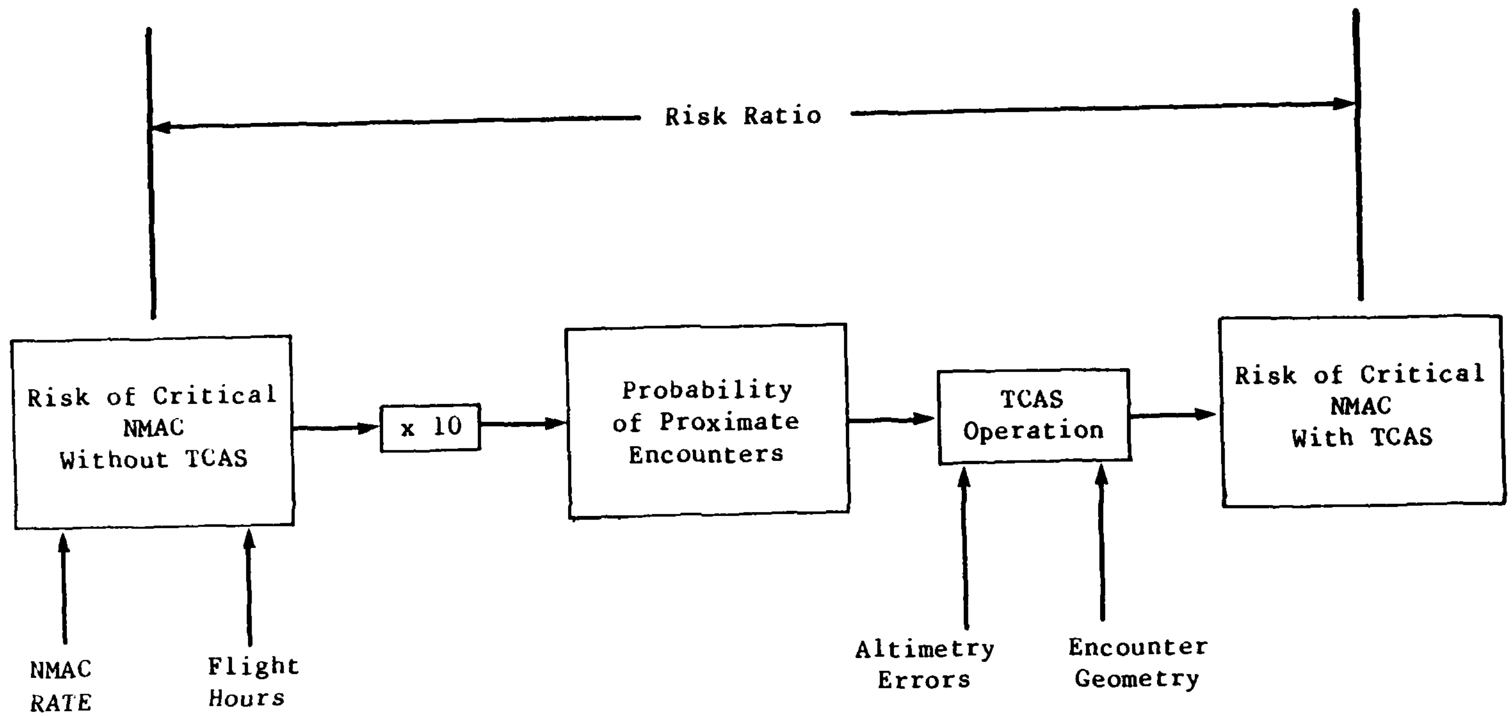
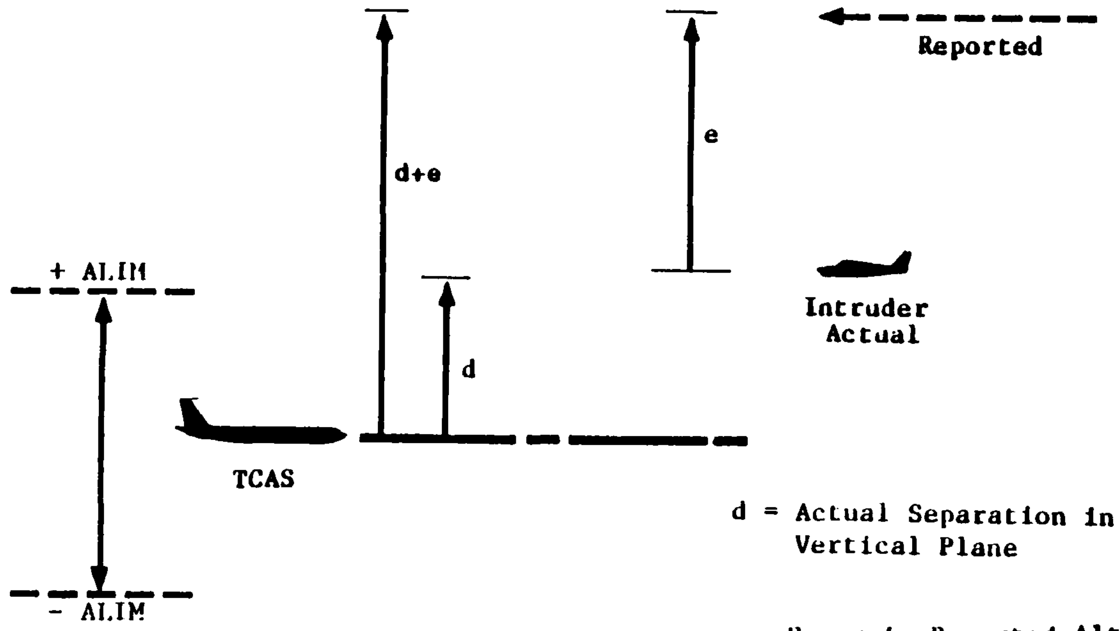



**FIGURE 4-1**
**RISK RATIO DUE TO ALTIMETRY ERROR**




d = Actual Separation in Vertical Plane

e = Error in Reported Altitude

**d+e = Apparent Separation**

NOTE: (1) Data recorded from Piedmont Phase I flight indicates that the distribution in d is uniform.

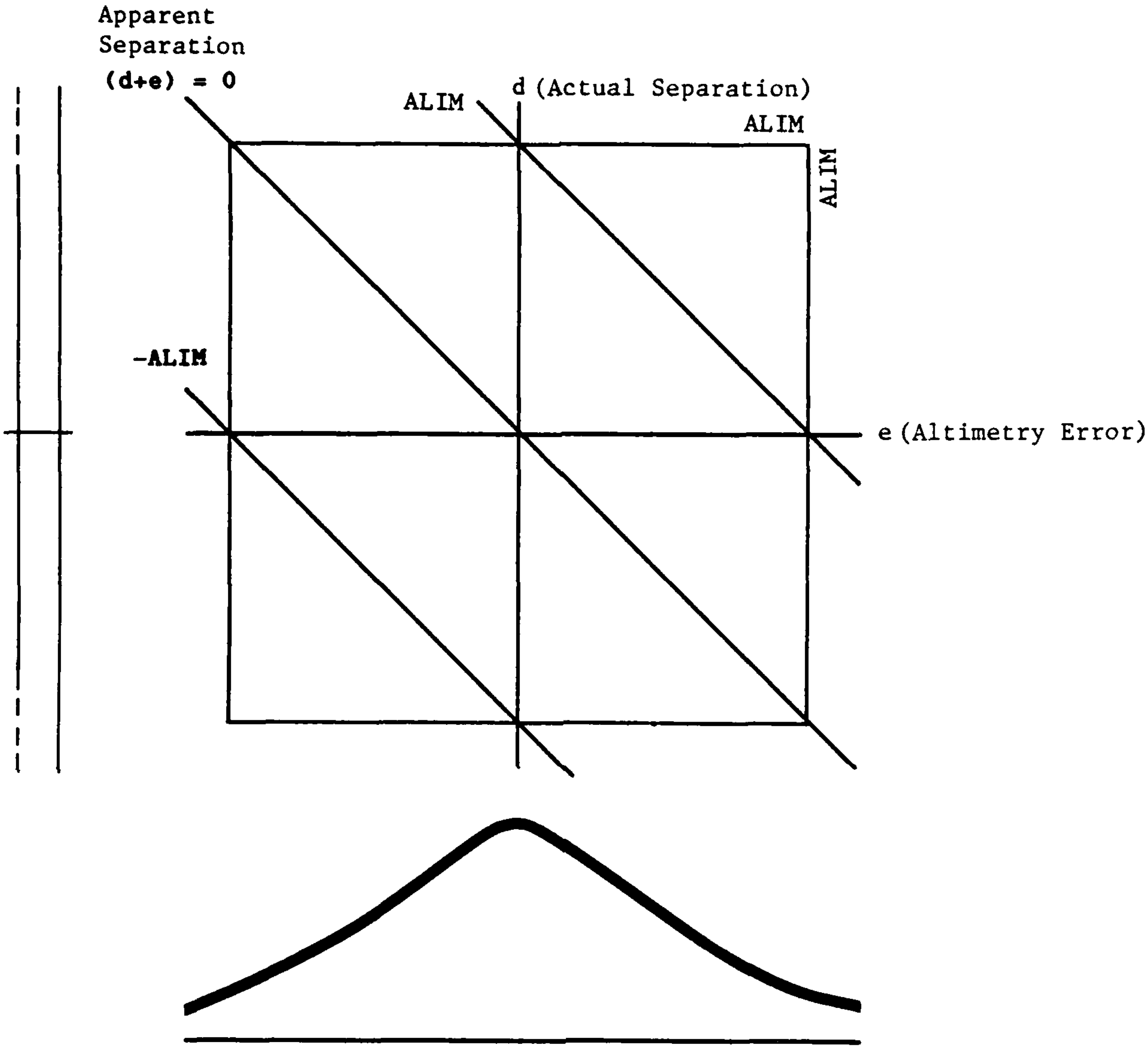
(2) Level encounters are used as examples, encounters with vertical rates also apply with d being referred to predicted closest point of approach.

**FIGURE 4-2**
**ENCOUNTER GEOMETRY**

d, increased to the parameter ALIM (plus some margin), at which time the RA changes from corrective to preventive. The time available for this maneuver is TAU seconds. In actual operation the true separation, d, is not known, only the apparent separation (d+e). The rules are the same as just described, but the effect depends on the magnitude of the error.

To help understand and evaluate this effect, we plot the true separation and the error as in Figure 4-3, the d-e plane. The ordinate, d, is the actual vertical separation. On the left side of the figure the distribution of d is shown as being uniform, as was found in Section 3. The abscissa, e, is the altimetry error. Its distribution, illustrated at the bottom of the figure, is shown as Gaussian with a zero mean and a standard deviation of sigma, the latter being evaluated as the square root of the sum of the squares of own error, intruder error, and tracking bias error. The approach will be to define those regions which could lead to less than 100 ft separation (an NMAC).

The lines shown on the d-e plane are of importance when considering the relation between the actual encounter geometry and the Resolution Advisory when it is first posted. The horizontal lines at $\pm$ ALIM are the nominal objectives for separation that TCAS is intended to achieve. The vertical lines at $\pm$ ALIM indicate values of error in reported altitude of this magnitude. The diagonal lines denote constant values of apparent separation (before the TCAS aircraft starts a corrective maneuver) as determined for various degrees of erroneous altimetry.




$$f(e) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\,\frac{e^2}{\sigma^2}\right)$$

**FIGURE 4-3**
**THE D-E PLANE**

Figure 4-4 is a repeat of the previous figure, but with some additional regions identified. The two horizontal lines at $d = \pm 100$ ft define the extent of NMACs without TCAS -- the aircraft come within 100 ft and the altimetry error is not a factor.

In the shaded areas, the error is in the direction opposite to the separation and of a larger magnitude, so that an intruder actually above the TCAS will appear below, and vice versa. That is, e is less than -d for d greater than 0, and e is greater than -d for d less than 0. Advisories occurring in these regions provide a "wrong way" direction, which may or may not lead to an NMAC, as will be shown. In unshaded areas between the diagonal lines the error is in the same direction as the separation, and so has no effect on the fault mechanisms of TCAS. Outside of the diagonal lines positive (corrective) advisories are not generated since the reported separation (d+e) appears larger than ALIM.

### 4.2.2 Preliminary Analysis

The effects of altimetry error on TCAS can now be illustrated. Figure 4-5a shows the cross hatched regions where the error is such that, if an NMAC were to occur, it would not be resolved. Outside of the diagonal lines the error is so great that, even though the true separation (d) is within 100 ft (an NMAC without TCAS), the apparent separation (d+e) is greater than ALIM, so no corrective RA is given. Inside the diagonal lines, the apparent separation is within ALIM and a corrective RA is given, but it will be prematurely removed before d exceeds 100 ft. The unshaded regions between $d = \pm 100$ ft are where TCAS does resolve NMACs, as intended.

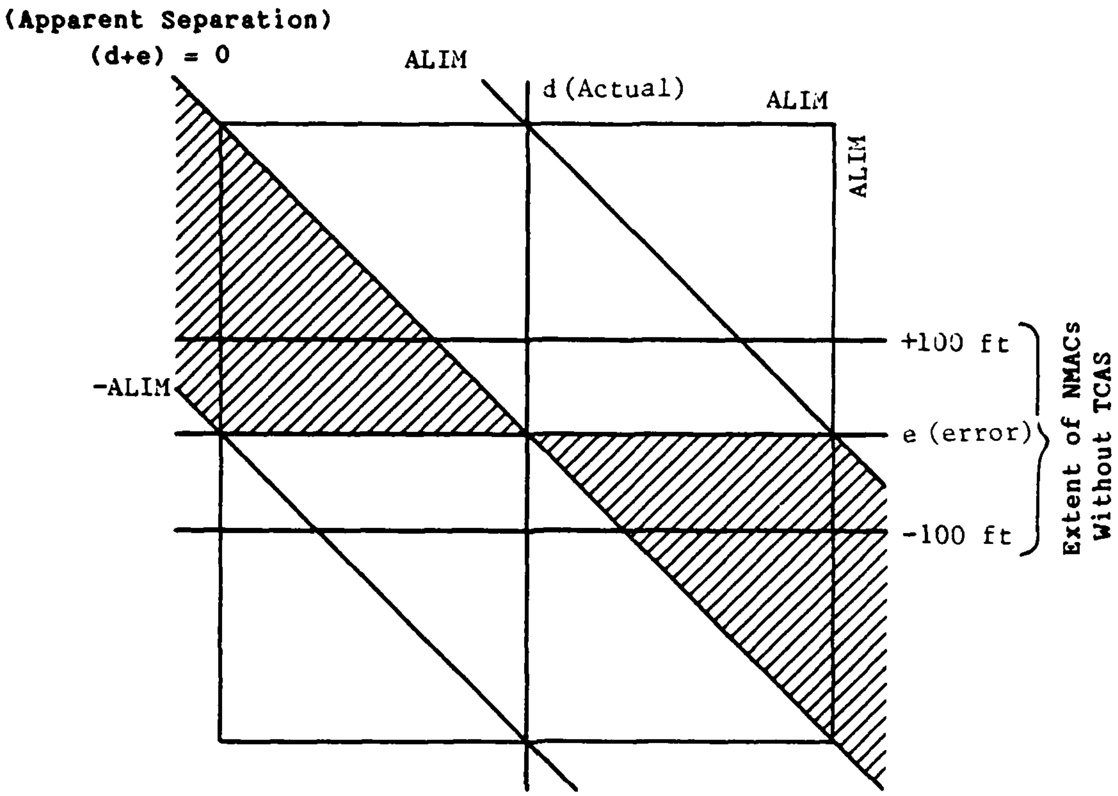
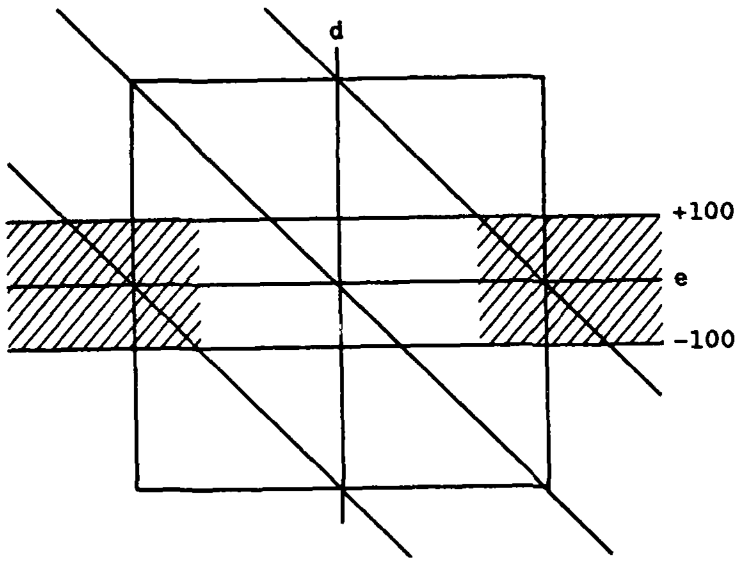
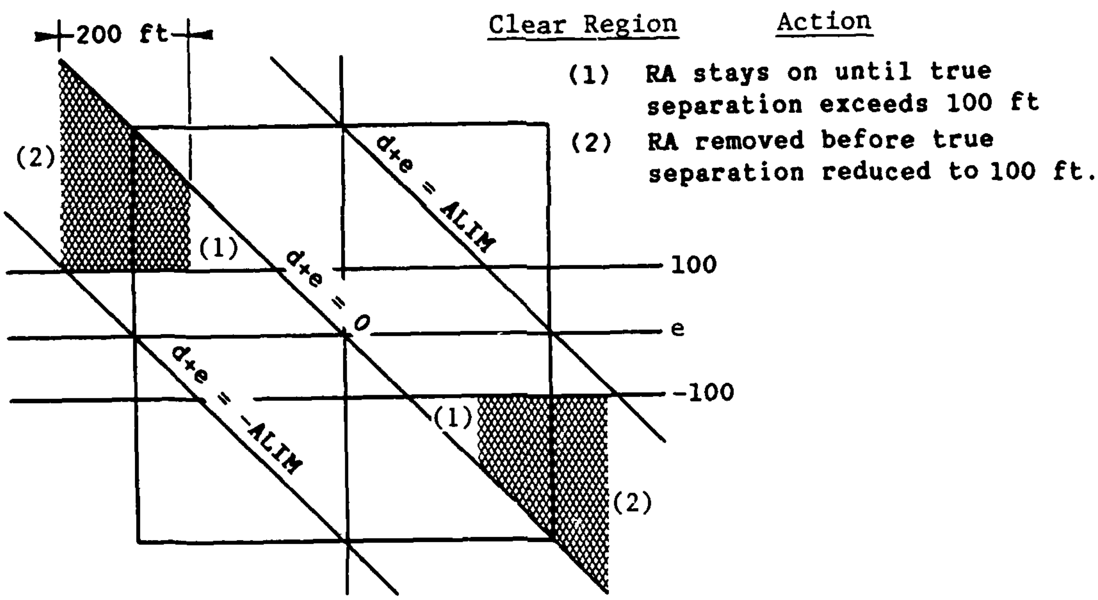



**FIGURE 4-4**
**REGIONS OF "WRONG-WAY" ADVISORIES**




(a) Regions Where TCAS Fails to Resolve a Critical NMAC



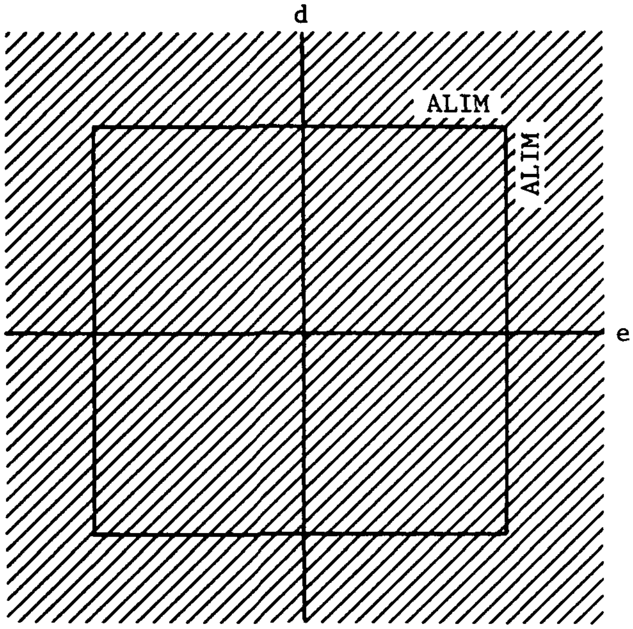

(b) Regions Where TCAS Would Induce a Critical NMAC

**FIGURE 4-5**
**REGIONS OF ALTIMETRY FAILURE**

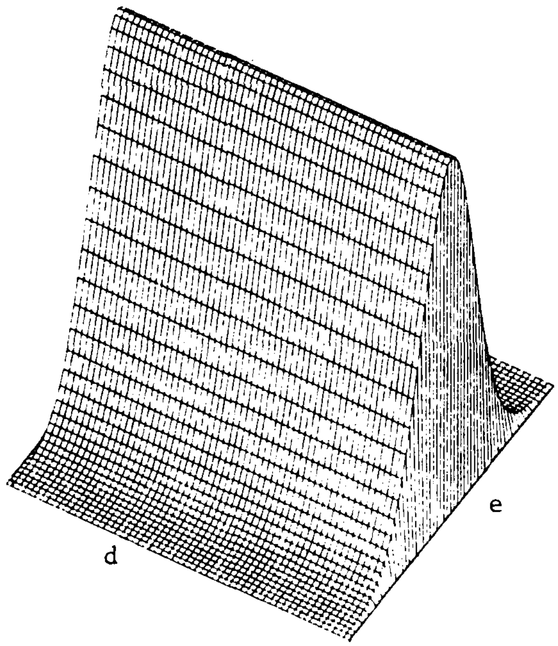
The more serious concern, that of TCAS inducing an NMAC, is illustrated by the shaded regions in Figure 4-5b. For these regions, the intruder appears to be in the opposite direction of his true separation, which originally was greater than 100 ft (i.e., would not have constituted a critical near midair collision). The width of shaded regions along the e axis is ± 100 ft. If the error is less than the value at the region boundary (|e| less than (ALIM-100)), a "wrong way" advisory occurs, but it stays posted until the true separation is greater than 100 ft (unshaded regions 1). If the error is larger (|e| is greater than (ALIM+100)), d is initially large, and the wrong way advisory is removed before the separation decreases to 100 ft (unshaded regions 2).

One more step remains before we are ready to apply these concepts to calculate the Risk Ratio -- we must determine the relative probability of being at any point in the d-e plane. Figure 4-6 illustrates the approach already implied. Figure 4-6a is a section of the plane that covers the region of interest -- we used ± 1000 ft in the vertical dimension and ± 1000 ft error. Figure 4-6b plots the distribution -- uniform in d and Gaussian in e. (The figure has been rotated and tilted to make the three-dimensional effect more apparent.) The integral (volume) of Figure 4-6b is essentially unity. (For practical purposes, all possible events occur within the ±1000 ft by ±1000 ft square.)

The first step in computing the Risk Ratio is to normalize all effects to the situation that exists without TCAS. This is done in Figure 4-7. All proximate encounters that come within the ±100 ft altitude band shown are the NMACs that occur in the absence of TCAS. The volume of Figure 4-7b is, of course,

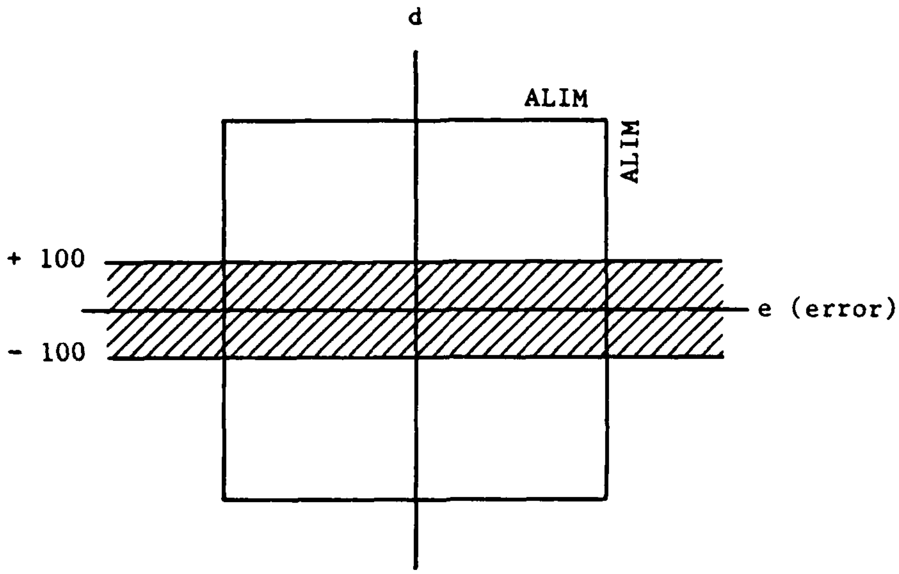



(a) Coordinates

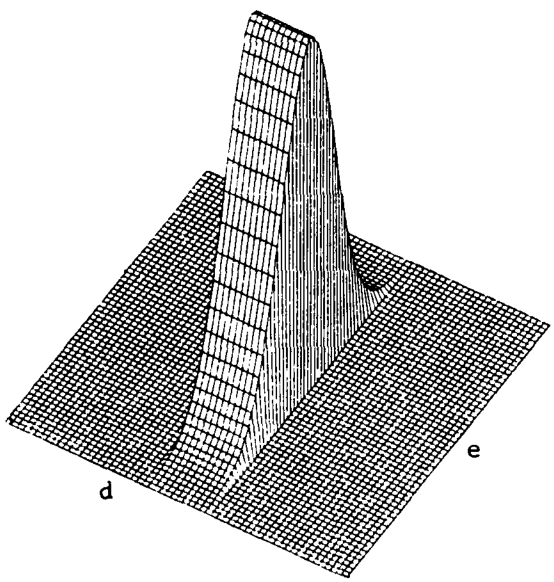



(b) Probability

**FIGURE 4-6**
**PROBABILITY DISTRIBUTIONS ON THE D-E PLANE**




(a) Region for Critical NMAC




(b) Error Contours

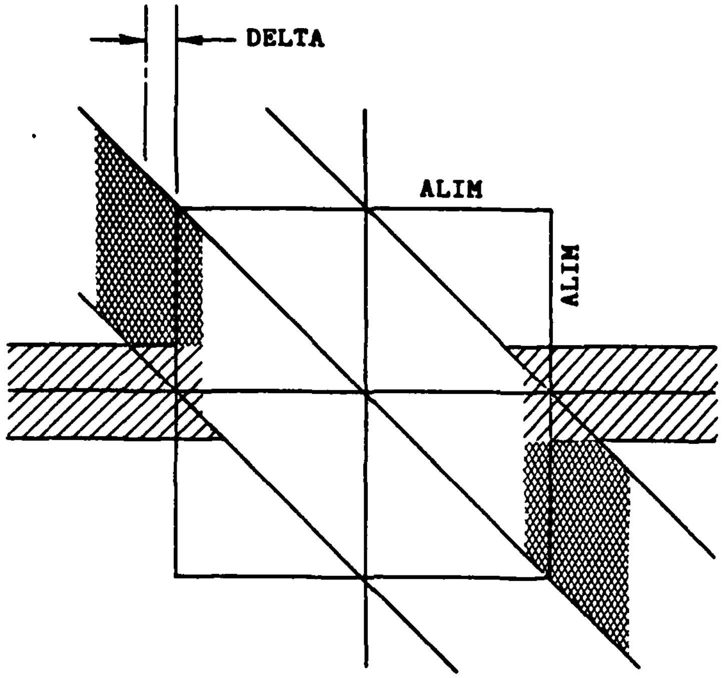
**FIGURE 4-7**
**ERROR CONTOURS WITHOUT TCAS**

one-tenth of Figure 4-6b, and will be used to normalize all further cases.

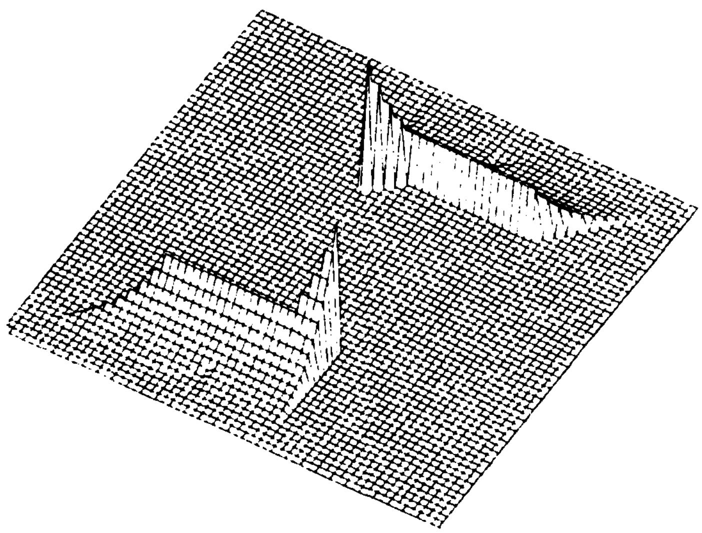
Figure 4-8 shows the regions on the d-e plane where altimetry errors defeat TCAS operation. The cross hatched regions in Figure 4-8a are those in which TCAS does not prevent an NMAC from occurring. The dark gray regions are those in which TCAS could induce an NMAC. For purposes of illustration, this figure was drawn for the case of ALIM = 340 ft, sigma = 150 ft, and the advisory is kept posted until an indicated separation of ALIM +75 ft is achieved. Keeping the advisory posted for indicated separations DELTA (a parameter in the logic) larger than ALIM moves the grey regions out to the lower probabilities, and so achieves a reduction in the Risk Ratio, which is computed as the volume of Figure 4-8b divided by that of Figure 4-7b. Increasing ALIM would also reduce the Risk Ratio, but too much an increase would also increase the unwanted alarm rate. Figure 4-9 is a plot of the Risk Ratio with varying amounts of DELTA.

As a contrast, if the corrective advisory were retained until the TCAS aircraft achieves a fixed vertical displacement of DISP ft, the situation changes as shown in Figure 4-10. These figures have been drawn for ALIM = 340 ft, sigma = 150 ft, and DISP = 340 ft. The region in which TCAS can induce an NMAC is located in lower probability regions. Figure 4-11 is a plot of the Risk Ratio for different values of displacement.

When using the techniques of the fault tree, in Section 7, we will evaluate separately the probabilities of TCAS not resolving an NMAC and of TCAS inducing an NMAC. Further, to be consistent throughout the evaluation, we compare all faults to




a) Regions of Susceptibility



b) Error Contours

**FIGURE 4-8**
**ALTIMETRY ERROR CONTOURS**

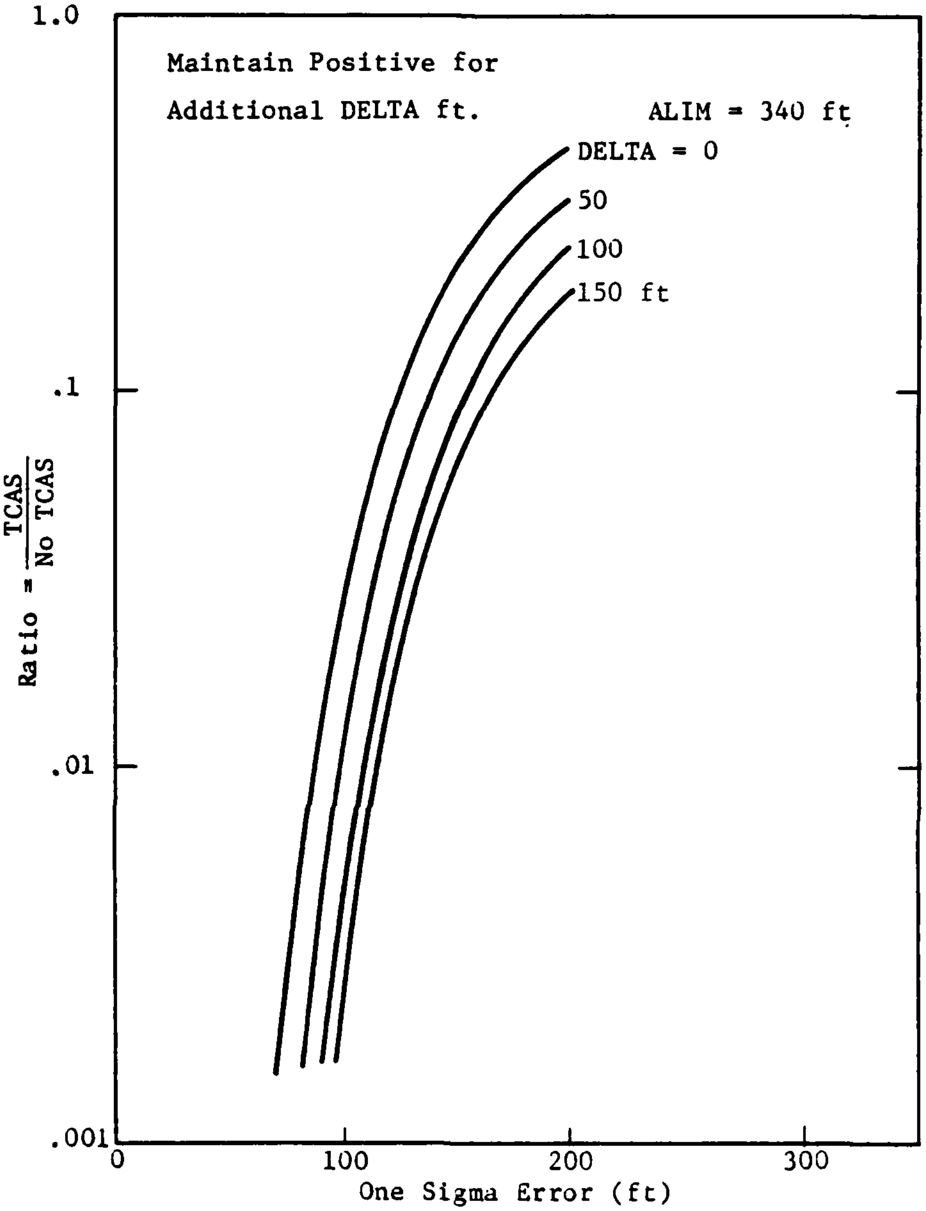
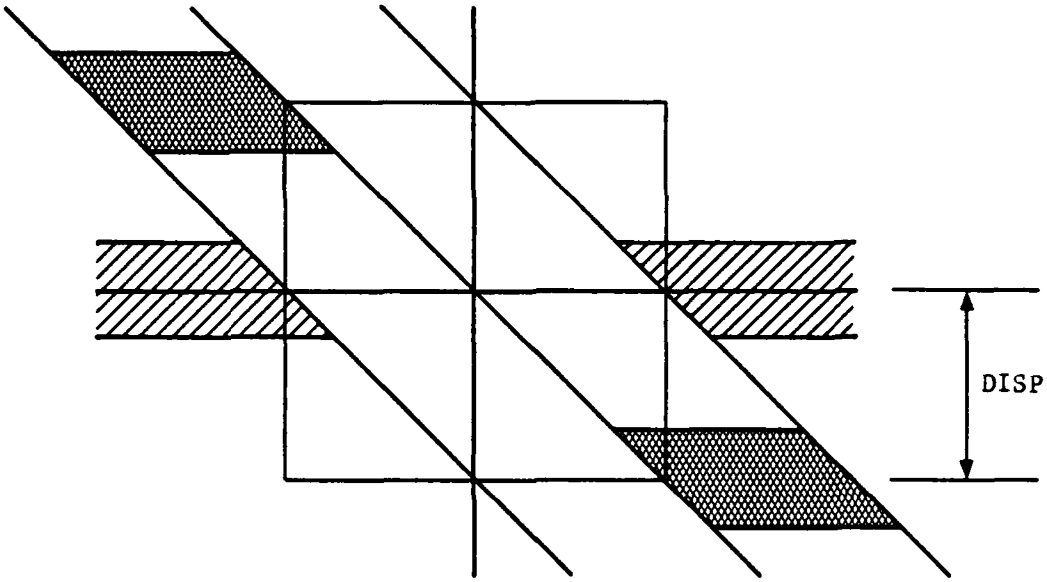
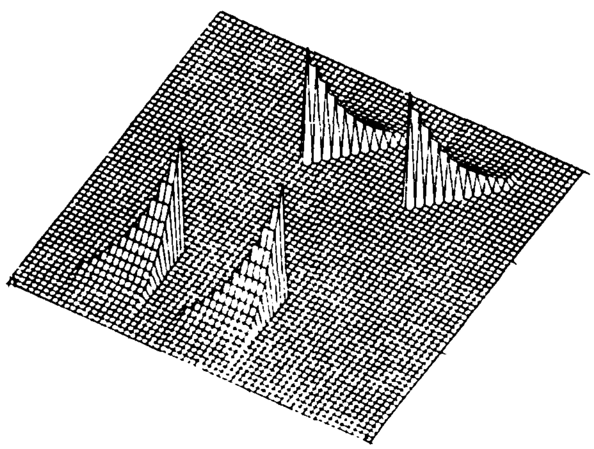



**FIGURE 4-9**
**VARIATION OF RISK RATIO WITH DELTA**




(a) Regions of susceptibility



(b) Error Contours

Note: Upon receipt of positive advisory, achieve a displacement of DISP feet.

**FIGURE 4-10**
**ALTIMETRY ERROR CONTOURS FOR CONSTANT DISPLACEMENT**

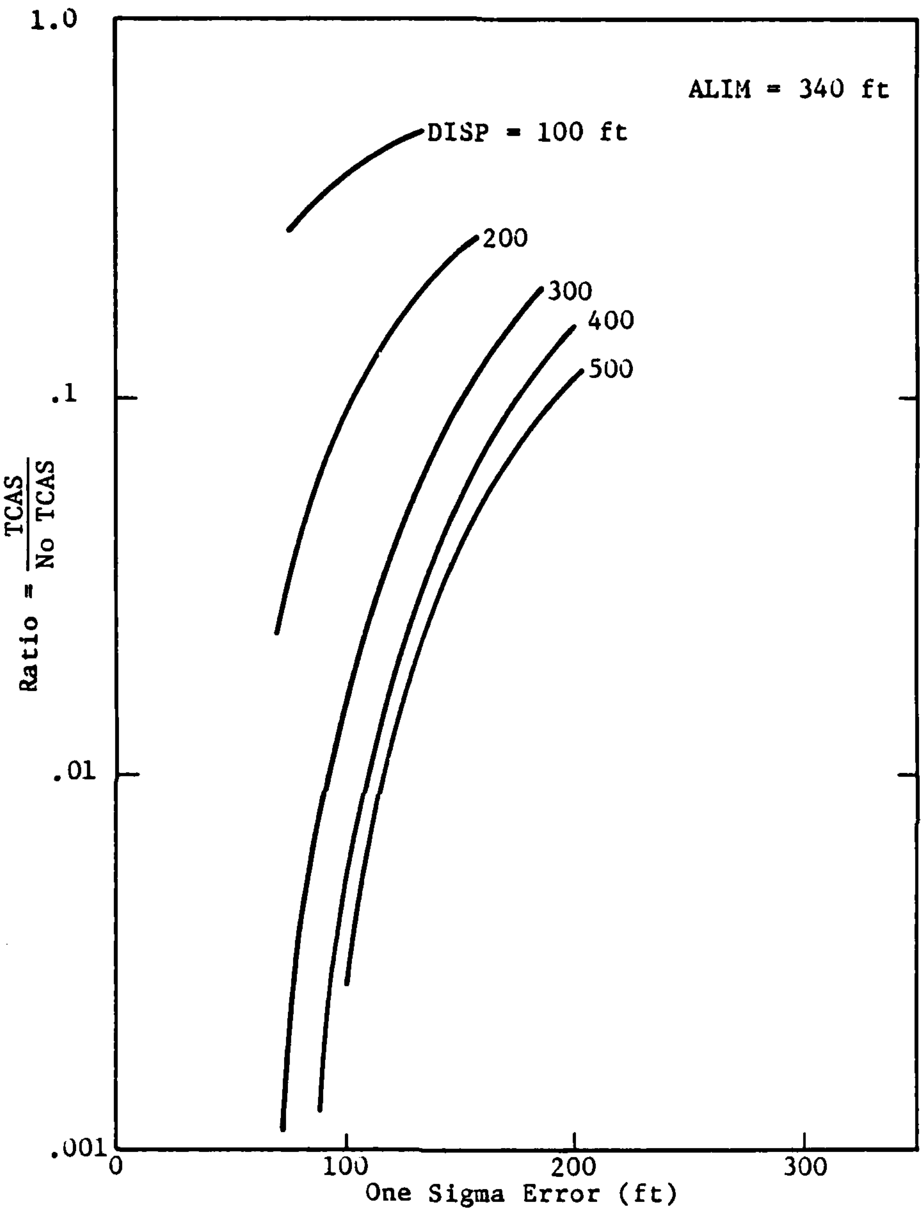



**FIGURE 4-11**
**VARIATION OF RISK RATIO WITH FIXED DISPLACEMENTS**

to the same basis, an NMAC in the absence of TCAS (i.e., Risk Ratio).

#### 4.2.3 Limited Maneuver Capability

All the preceding discussion assumes that the aircraft actually moves the desired amount. For example, if the error is zero and the aircraft are coaltitude, the TCAS advisory would remain on until a displacement of ALIM + DELTA is achieved. Under some conditions it is possible that the aircraft may not be able to achieve that displacement in the time available (TAU seconds). However, there will often be some initial separation, so less displacement than ALIM would suffice. Also, less displacement may still suffice as long as it prevents the critical NMAC (greater than 100 ft separation).

Thus, new regions on the d-e plane would become failures if the aircraft cannot maneuver the desired amount. The effect of a limited maneuver capability can be calculated as an additional Risk Ratio, to be added to that caused by altimetry error. Figure 4-12 shows this additional Risk Ratio as a function of the achievable displacement to vertical rate for a given TAU. For this scale, a delay of five seconds and an acceleration of 1/4 g from level to a constant vertical velocity was assumed. For example, if 500 ft were the desired displacement objective and only 450 ft could be attained (approximately 1500 fpm would provide 450 ft in 25 seconds), there would be very little loss, about .001, or .1 percent. However, if only 400 ft were obtained, the loss would add 1 percent to the Risk Ratio.

#### 4.2.4 Evaluation

Having established the relationships between the various factors of TCAS performance and altimetry error, we are now in

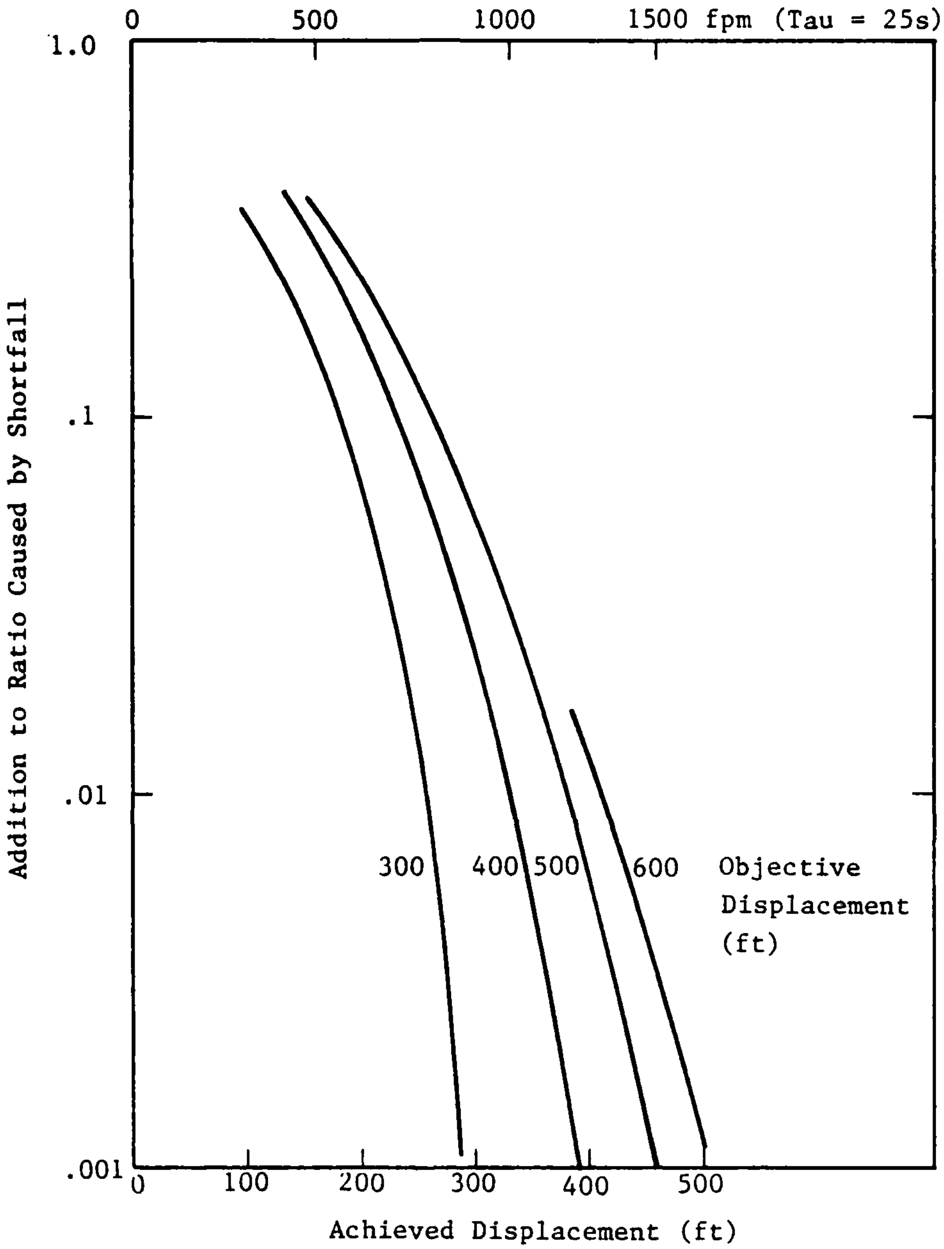



**FIGURE 4-12**
**EFFECT OF LIMITED MANEUVER CAPABILITY**

a position to obtain the values of some probabilities to be used in the TCAS fault tree.

In Appendix K an extensive evaluation of the standard deviation of altimetry error is made. There it is shown that there are two principal characterizations of error depending on whether the system does or does not have compensation for various errors (principally static source error). Specifically, the air data computer corrected altimetry systems often provide altimetry data in conformance with the performance standards specified in the ARINC Characteristics for Air Data Systems (References 18-22). Baseline altimetry system equipment, on the other hand, is largely controlled by the Federal Aviation Regulations (FARs) and is found primarily among GA aircraft. Tables 4-1 and 4-2, repeated from Appendix K, provide the standard deviations of altimetry error for the corrected and non-corrected systems, respectively.

#### 4.2.4.1 Basic Conditions

The data on altimetry error, together with a numerical integration of the error probabilities, as discussed in the preceeding section, provide the desired results. This evaluation will assume the TCAS altimetry error to be described by the air carrier results, and the intruder error to be of general aviation quality. We RSS the TCAS altimetry error, the intruder altimetry error, and a 150 fpm tracking bias error, the latter being equivalent to a safety margin. Then performing the integration produces the results in Table 4-3.

The resulting effect depends on altitude, both because of the gradual increase of altimetry error with altitude and because of the stepped thresholds (ALIM), which were introduced to

TABLE 4-1
ESTIMATED STANDARD DEVIATION IN TOTAL ALTIMETRY SYSTEM
PERFORMANCE AMONG SELECTED ADC CORRECTED ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FT) | STATIC SOURCE | TRANSDUCER | QUAN. (MODE C) | TOTAL STD. DEV. (FT.) W/O Mode C | W/Mode C |
|---|---|---|---|---|---|
| SL | 31 | 12 | 30 | 33 | 45 |
| 5 K | 36 | 12 | 30 | 38 | 48 |
| 10 K | 41 | 12 | 30 | 43 | 52 |
| 15 K | 46 | 19 | 30 | 50 | 58 |
| 20 K | 52 | 25 | 30 | 58 | 65 |
| 25 K | 57 | 31 | 30 | 65 | 71 |
| 30 K | 61 | 38 | 30 | 72 | 78 |
| 35 K | 68 | 44 | 30 | 81 | 86 |
| 40 K | 75 | 50 | 30 | 90 | 95 |

TABLE 4-2
ESTIMATED STANDARD DEVIATION IN TOTAL ALTIMETRY SYSTEM
PERFORMANCE AMONG BASELINE ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FEET) | STATIC SOURCE | TRANSDUCER | QUAN.- (MODE C) | TOTAL STD. DEV. (FT.) W/O Mode C | W/Mode C |
|---|---|---|---|---|---|
| SL | 78 | 26 | 63 | 82 | 104 |
| 5 K | 95 | 29 | 63 | 99 | 118 |
| 10 K | 109 | 38 | 63 | 115 | 132 |
| 15 K | 125 | 45 | 63 | 132 | 147 |
| 20 K | 140 | 52 | 63 | 149 | 162 |
| 25 K | 155 | 61 | 63 | 166 | 178 |
| 30 K | 168 | 69 | 63 | 182 | 192 |
| 35 K | 185 | 77 | 63 | 200 | 210 |
| 40 K | 200 | 86 | 63 | 218 | 227 |

TABLE 4-3
EFFECTS OF ALTIMETRY ERRORS

| ALT. | ALIM | RSS ERROR (SIGMA) | RISK RATIO | FRACTION OF NMAC IN ALTITUDE BAND | WEIGHTED RISK RATIO |
|---|---|---|---|---|---|
| 5 Kft | 340 ft | 143 ft | .0744 | .44 | .0327 |
| 10 | 340 | 156 | .1141 | .31 | .0354 |
| 15 | 440 | 175 | .0554 | .17 | .0094 |
| 20 | 640 | 190 | .0051 | .03 | .0002 |
| 25 | 640 | 206 | .0117 | .01 | .0001 |
| 30 | 640 | 220 | .0210 | .03 | .0006 |
| 35 | 740 | 239 | .0125 | .01 | .0001 |

Total = .0785
Unresolved = .0388
Induced = .0397

Notes: Errors are 1. Own altimetry (A/C Quality)
2. Intruder altimetry (GA Quality)
3. 150 fpm tracking bias error

DELTA = 75 ft (Corrective advisory is maintained until the apparent separation is ALIM + 75 ft)

account for that phenomenon. The probability of an NMAC occurring within the noted altitude bands was obtained from the data in Section 3.1.1. It can be seen that, if all intruders had uncorrected altimetry, the number of NMACs would drop to about 8 percent of those that occur in the absence of TCAS. About half of these would have been induced by TCAS.

After analyzing the results, it appeared desirable and convenient to obtain a substantial improvement by a modest change to the parameter ALIM. (The parameter DELTA already is 75 ft.) The values of ALIM would increase from 340 ft to 400 ft, when the encounter is at an altitude less than 10,000 ft; and from 440 ft to 500 ft when the altitude is between 10,000 ft and 18,000 ft. The values at higher altitudes need not be altered, as they make a very small contribution to the total risk. The result, as shown in Table 4-4, is that the number of NMACs would further decrease to 3 percent of those that occur in the absence of TCAS; about half of these would be induced failures and half would be NMACs that were not resolved.

#### 4.2.4.2 Exponential Error Assumption

A key assumption in the evaluation of the effect of altimetry error is the Gaussian form of the error distribution. If, instead, one were to assume the rather extreme double-sided exponential distribution with the same standard deviation (heavier weighting of the tails of the distribution), we could see the impact of this assumption. This means changing from the previously given expression,

$$f(e) = \frac{1}{\sigma\sqrt{2}} \quad \exp\left(-\frac{1}{2} \quad \frac{e^2}{\sigma^2}\right)$$

TABLE 4-4
EFFECTS OF ALTIMETRY ERROR FOR MODIFIED ALIM

| ALT. | ALIM | RSS ERROR (SIGMA) | FRACTION OF NMAC IN ALTITUDE BAND | RISK RATIO | WEIGHTED RISK RATIO |
|---|---|---|---|---|---|
| 5 Kft | 400 ft | 143 ft | .44 | .0269 | .0118 |
| 10 | 400 | 156 | .31 | .0485 | .0150 |
| 15 | 500 | 175 | .17 | .0231 | .0039 |
| 20 | 640 | 190 | .03 | .0051 | .0002 |
| 25 | 640 | 206 | .01 | .0117 | .0001 |
| 30 | 640 | 220 | .03 | .0210 | .0006 |
| 35 | 740 | 239 | .01 | .0125 | .0001 |

Total = .0317
Unresolved = .0143
Induced = .0174

Notes: Errors are
1. Own altimetry (A/C Quality)
2. Intruder altimetry (GA Quality)
3. 150 fpm tracking bias error

DELTA = 75 ft (Corrective advisory is maintained until the apparent separation is ALIM + 75 ft)

to the following:

$$f(e) = \frac{1}{\sigma\sqrt{2}} \quad \exp\left(- \sqrt{2}\,\frac{|e|}{\sigma}\right)$$

When this is done, the result is as shown in Table 4-5, somewhat more than twice the probability of the Gaussian assumption.

#### 4.2.4.3 Air Carrier Intruder

If the intruder is an air carrier aircraft instead of a GA aircraft, its altimetry is characterized by Table 4-1 instead of Table 4-2. The resulting improvement in the total RSS error reduces the Risk Ratio by an order of magnitude or more.

### 4.2.5 Altimetry Error Summary

In Section 3.1 it was shown that GA and "other" aircraft constitute about 79 percent of the critical NMAC incidents. Using the results of Table 4-4 with that weighting factor, we arrive at the conclusion that, overall, the Risk Ratio introduced by altimetry errors is .025. The unresolved component is .011, and the induced component is .014.

## 4.3 Effects of Maneuvering Intruders

One of the principal concerns of the TCAS environment is the problem of an intruder that makes a sudden maneuver just when TCAS is about to compute its Resolution Advisory. The intruder maneuver could take place either shortly before or after TCAS declares the intruder a threat. Several distinct classes of encounter geometries are illustrated in Figures 4-13, 4-14, and 4-15. Figure 4-13 represents the geometry often called the "classical fake-out" maneuver. In this situation, TCAS is

TABLE 4-5
EFFECTS OF ALTIMETRY ERROR FOR ASSUMED EXPONENTIAL ERROR DISTRIBUTION

| ALT. | ALIM | RSS ERROR (SIGMA) | FRACTION OF NMAC IN ALTITUDE BAND | RISK RATIO | WEIGHTED RISK RATIO |
|---|---|---|---|---|---|
| 5 Kft | 400 ft | 143 | .44 | .0650 | .0286 |
| 10 | 400 | 156 | .31 | .0867 | .0269 |
| 15 | 500 | 175 | .17 | .0627 | .0107 |
| 20 | 640 | 190 | .03 | .0344 | .0010 |
| 25 | 640 | 206 | .01 | .0477 | .0005 |
| 30 | 640 | 220 | .03 | .0607 | .0012 |
| 35 | 740 | 239 | .01 | .0483 | .0003 |

Total = .0692
Unresolved = .0296
Induced = .0396

Notes: Errors are
1. Own altimetry (A/C Quality)
2. Intruder altimetry (GA Quality)
3. 150 fpm tracking bias error

DELTA = 75 ft (Corrective advisory is maintained until the apparent separation is ALIM + 75 ft)

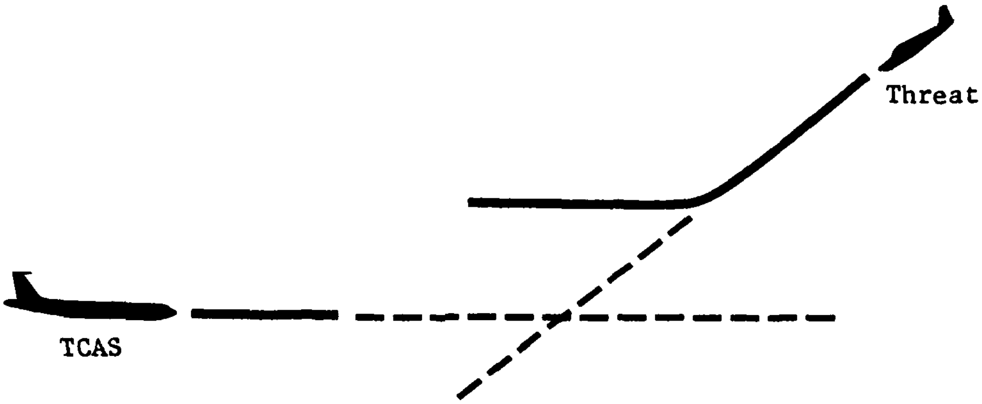



**FIGURE 4-13**
**CLASSICAL FAKE-OUT MANEUVER**

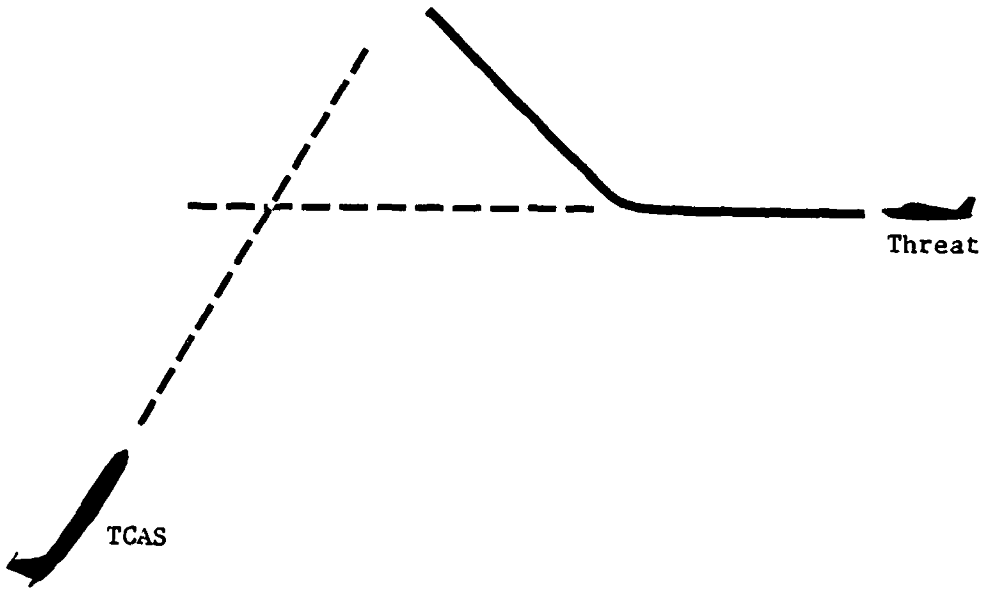



**FIGURE 4-14**
**INTRUDER INITIATED MANEUVER IN DIRECTION OF TCAS RATE**

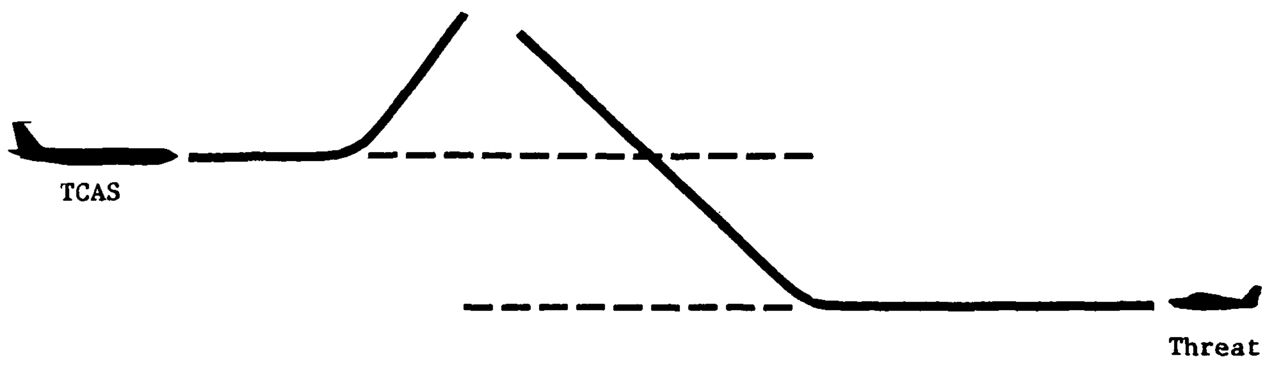



**FIGURE 4-15**
**INTRUDER INITIATED MANEUVER IN DIRECTION OF TCAS MANEUVER**

essentially level, while the threat is converging with a vertical rate sufficiently high so as to project an altitude crossing before the two aircraft reach their closest point of approach. The TCAS logic models its "climb" and "descend" escape maneuvers* and selects the one giving greater separation. In this case, the maneuver moves TCAS toward the threat's initial altitude. There is no hazard so long as the the threat continues its vertical rate for the remainder of the encounter (typically 25 seconds). However, if the threat levels off in that time period, the TCAS escape may lead to an NMAC. In retrospect, the TCAS advisory was in the wrong direction, but at the time of sense selection, the intruder maneuver was not anticipated and the escape appeared to be in the best direction.

Figure 4-14 shows a different case, in which the TCAS aircraft has a vertical rate. If the TCAS advisory reinforces the rate (a "preventive" positive, or "maintain rate"), TCAS cannot reasonably be faulted if an adverse intruder maneuver causes an NMAC, since the pilot had already selected the maneuver. In Figure 4-15, the TCAS aircraft may initially be level, as shown, or may have a vertical rate. If TCAS acts to maintain or to increase the existing separation, a natural resolution, the intruder may still maneuver adversely and cause an NMAC. Again, TCAS took the proper action. It should be noted that this case generally requires a substantial maneuver by the intruder, in order to overcome the initial separation and the TCAS escape maneuver, and still cause an NMAC.

---

*In this section, flight regimes where TCAS cannot climb or cannot descend are not considered.

The first, or "fake-out" case, is the one analyzed in this report. The conditions leading to this scenario, and the probability of its occurrence, are discussed in the subsections that follow.

### 4.3.1 TCAS Tracking of Intruder Altitude Rate

The task of the vertical tracker is a difficult one -- altitude reports from a threat aircraft are quantized to 100 ft intervals; reports may be missed, or rejected if corrupted by noise. The current design was first proposed by M.I.T. Lincoln Laboratory. This design is an inverse tracker, in a sense, because it estimates the altitude rate by tracking the time between the 100-foot altitude changes. The design takes into account several patterns of altitude reports observed in test data, and provides a confidence indicator called "firmness." While the tracker always attempts to classify each track (such as level, climbing, or descending) and make a best estimate of rate, there are certain patterns, typically accelerations, for which the quantized reports are difficult to track. That is, a wide range of true rates could produce the observed sequence of reports. Several more seconds of reports normally clarifies the situation and reduces the potential error in tracked rate. The firmness indicator tells when this potential error is large, and the resulting confidence in tracked rate is low. Under these conditions, the detection and resolution functions of the logic defer important decisions, principally the selection of sense.

Figure 4-16 illustrates the state of the TCAS vertical tracker when the intruder maneuvers. The solid line represents the intruder's true vertical profile as a function of time. (TCAS, however, measures discrete-time samples of this profile

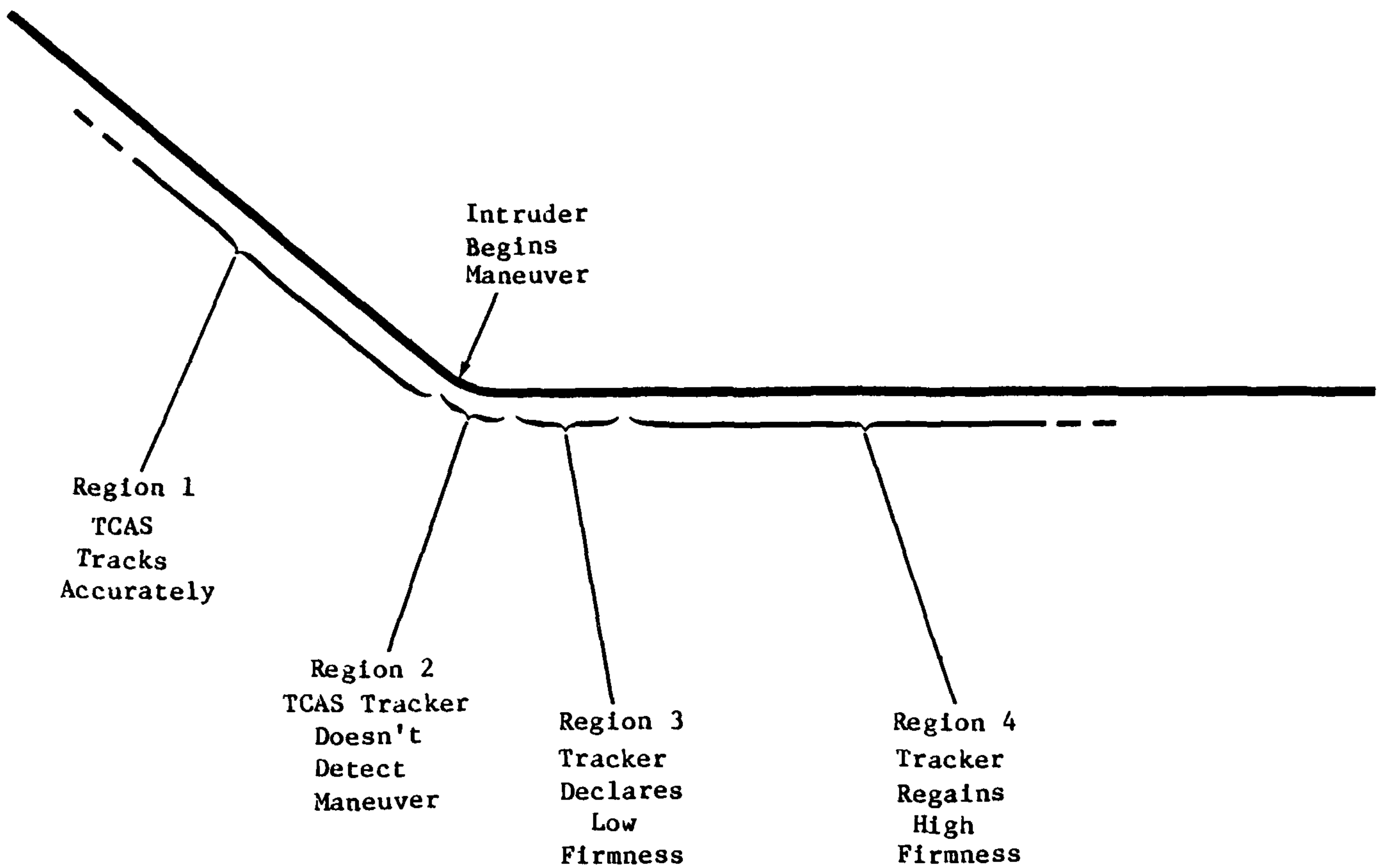



**FIGURE 4-16**
**STAGES IN TCAS TRACKING OF MANEUVER**

quantized to 100 ft.) Four regions are indicated to denote states of tracking, although the length of each depends upon the particular track details. Region 1 is the time before the maneuver, when TCAS is assumed to be tracking "accurately", with accuracy typical of a high value of firmness. Region 2 begins when the intruder aircraft begins to accelerate, and lasts until TCAS declares low firmness. During Region 2, TCAS may or may not begin to correct the tracked rate, but would not defer an advisory. Region 3 is the period of low tracker firmness. It normally extends beyond the conclusion of the actual maneuver. Region 4 begins when the tracker regains high firmness (confidence) in the new rate.

If the TCAS threat criteria are violated during Region 4, the maneuver is in the past, and has no effect. If the threat criteria are satisfied during Region 3, low firmness delays the advisory. In this case, the alert is late, but sense selection takes account of the maneuver. For some encounters, the alert is not delayed. If one maneuver will provide satisfactory separation against the entire spread of possible rates, that maneuver is selected immediately, despite the low firmness.

If the threat is declared during Regions 1 or 2, the TCAS maneuver is selected without knowledge of the threat maneuver, since it either has not begun or has not been recognized. Therefore, the extent of Region 2 is critical, since it extends the potential window for being foiled. Simulations for various rates and accelerations show that this interval is not very sensitive to the initial rate (for level-offs), but varies somewhat with acceleration: 3 to 6 seconds for .33g and above, versus 6 to 14 seconds for .15g. Considerable variation within these ranges was observed for repeated trials with the same rates and accelerations, varying only the absolute altitude within the 100 ft quantum. Maneuvers from level to a rate are detected at the first quantum change. This is typically 3 to 6 seconds.

### 4.3.2 Threat Detection and Resolution Logic

Irrespective of the limitations of tracking the maneuvers discussed in the previous section, the fake-out leading to an NMAC can only occur when certain other conditions are also satisfied. First, TCAS must select the sense calling for altitude crossing. Second, TCAS must select a positive advisory such that the TCAS aircraft would move toward the threat's final altitude.

These conditions occur only for certain encounter geometries, indicated in Figure 4-17. This figure depicts the detection and resolution decisions made by the logic as a function of the relative altitude and altitude rate of the intruder at the time of sense selection. The TCAS aircraft is assumed level.

Appendix J discusses this altitude-altitude-rate plane in more detail, and explains the results for each region as indicated in the figure. Many of the regions on this plane do not lead to altitude crossing. Of those advisories that do indicate altitude crossing, only the region indicated as "potential fake-out" gives a positive advisory, which will displace the TCAS.

The following sections evaluate the fraction of encounters that fall into this region, and estimate the probability that an intruder will also make the adverse maneuver.

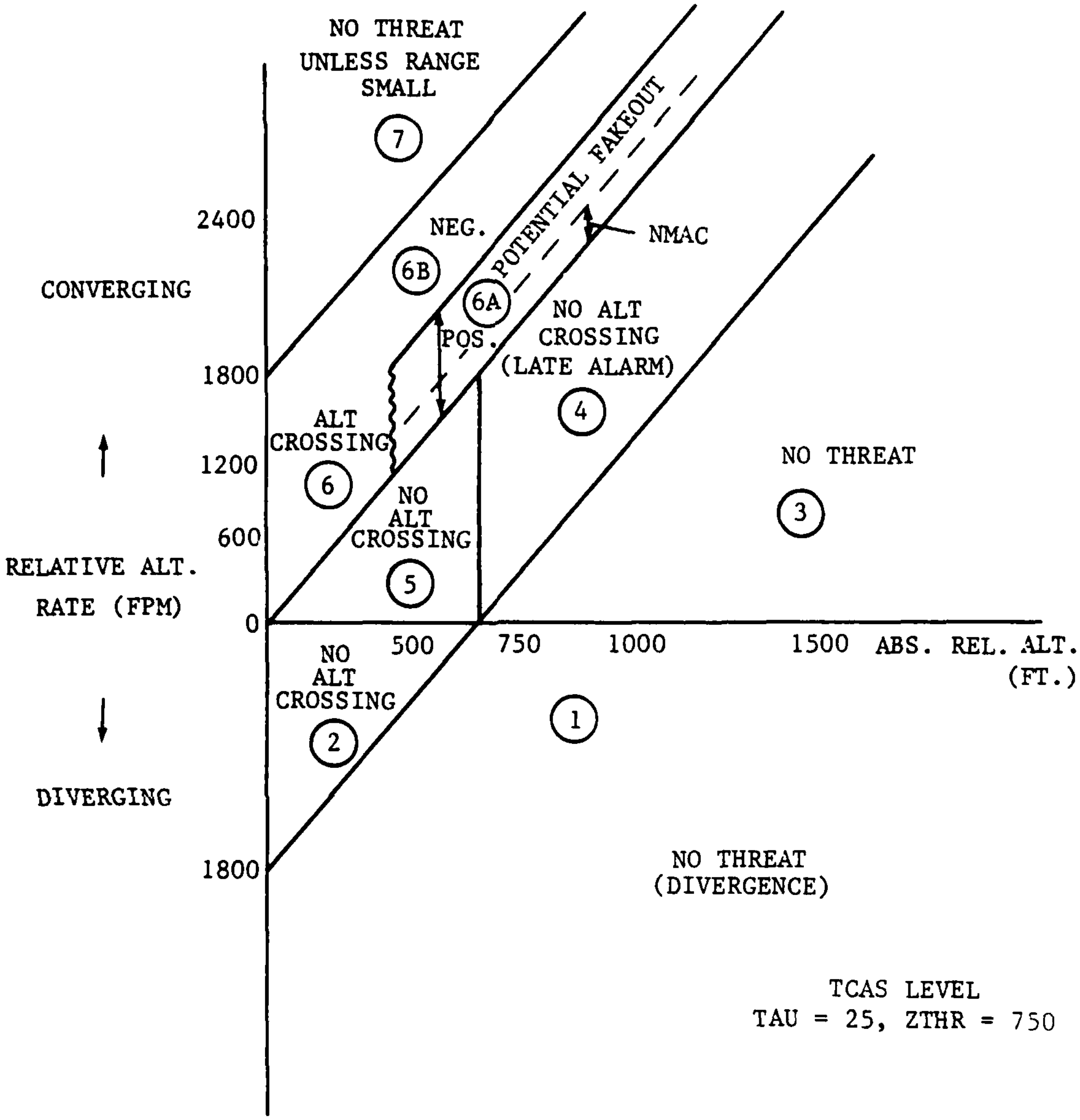



**FIGURE 4-17**
**SUSCEPTIBILITY OF TCAS TO FAKE-OUT**

### 4.3.3 Probability of Potential Fake-Out Scenarios

The previous discussion used Figure 4-17 to identify the combination of relative altitude and altitude rate which form potential fake-out scenarios. An important consideration is that all points on that figure do not occur with equal frequency. The environmental data will be used to determine a probability for the critical region.

Altitude rate data was categorized. Both in Piedmont data and FAA data, level tracks accounted for about 60 percent of all tracks. Of Piedmont tracks which generated advisories, about 70 percent were catagorized as level (less than 480 feet per minute), indicating that the use of all tracks is representative of advisories. The first two columns of Table 4-6 show vertical rate classifications (divided at 480 feet per minute intervals) and the frequency of such tracks in the Piedmont data for all tracks. These frequencies sum to 1.0 (100 percent). The fraction of resolution advisories with altitude-crossing sense is calculated by integrating over the altitude-crossing region (6A) the joint probability density function for a track's relative altitude and altitude rate; then dividing this by the corresponding integral taken over all regions giving resolution advisories (all regions except 1, 3, and 7).

P(alt. crossing advisory|advisory)

$$= \frac{\int p(\text{alt, alt rate})\ d(\text{alt})\ d(\text{alt rate})}{\int p(\text{alt, alt rate})\ d\ (\text{alt})\ d\ (\text{alt rate})}$$

TABLE 4-6
CALCULATION OF NMAC FROM MANEUVERING INTRUDER

| RATE (FPM) | FREQUENCY OF TRACK | POTENTIAL NMAC (A) | TIME ABOVE WINDOW | PROB NO ACCEL (B) | TIME IN WINDOW | PROB ACCEL (C) | PROB NMAC A x B x C |
|---|---|---|---|---|---|---|---|
| 3840 | .002 | .00046 | 16 | .56 | 3 | .11 | .000028 |
| 3600 | 0 | 0 | 16 | .57 | 3 | .11 | 0 |
| 3360 | .002 | .00046 | 15 | .58 | 4 | .12 | .000032 |
| 3120 | .004 | .00092 | 14 | .60 | 4 | .13 | .000072 |
| 2880 | .004 | .00092 | 13 | .62 | 4 | .14 | .000080 |
| 2640 | .008 | .00184 | 12 | .64 | 5 | .15 | .000177 |
| 2400 | .008 | .00184 | 11 | .67 | 5 | .16 | .000197 |
| 2160 | .008 | .00184 | 9 | .71 | 6 | .18 | .000235 |
| 1920 | .006 | .00138 | 7 | .76 | 6 | .20 | .000210 |
| 1680 | .022 | .00440 | 5 | .84 | 7 | .23 | .000850 |
| 1440 | .018 | .00234 | 2 | .94 | 8 | .26 | .000572 |
| 1200 | .028 | .00084 | 0 | 1 | 10 | .30 | .000252 |
| 960 | .06 | 0 | | | | | 0 |
| 720 | .10 | 0 | | | | | 0 |
| 480 | .122 | 0 | | | | | 0 |
| LEVEL | .60 | 0 | | | | | 0 |
| TOTAL | 1.0 | .017 | | | | | .00270 |

The integral in the numerator is taken over region 6. The integral in the denominator is taken over regions 2, 4, 5, and 6.

This can be approximated by calculating the area of horizontal strips in the plane of Figure 4-17, where the area of each strip is weighted by the frequency of the vertical rate corresponding to each strip. As noted earlier, flight data indicates a uniform distribution in relative altitude to some cutoff point. This will be approximated as uniform over the entire range of altitudes for which a resolution advisory is given. This approximation simplifies the mathematical tractability of the calculation. It will also be assumed that relative altitude and threat's altitude rate are independent. The equation then simplifies to:

P(alt. crossing advisory|advisory)

$$= \sum_{\text{all rates}} \frac{\text{width (alt. crossing regions)}}{\text{width (all advisory regions)}} \times p(\text{rate})$$

$$= .14$$

Observing that the high proportion of level encounters accounts for over 1/4 of this result, and that the TCAS tracker treats very low rates as level, the actual probability of altitude crossing sense should be between .10 and .14.

This calculation, made for all tracks, is consistent with an examination of individual advisories in the Piedmont data for which TCAS was level and the intruder was non-level. Fourteen percent of such advisories (mostly Traffic Advisories) were projected to cross in altitude (Section 3.2.1.3).

Of the scenarios in region 6, only those in region 6A would produce a positive advisory that could lead to an NMAC if the intruder maneuvered. Forming an expression similar to that above, but with the numerator restricted to region 6A,

$$P(\text{potential NMAC} \mid \text{advisory}) = \sum_{\text{all rates}} \frac{\text{width (region 6A)}}{\text{width (all advisory regions)}} \times p(\text{rate})$$

the results are tabulated in the third column of Table 4-6. The low rates are not considered part of region 6A, thus their contribution is zero. The total of this column is .017. Thus, 1.7 percent of all encounters could potentially be fake-out scenarios if the intruder levels out at the wrong time. To be conservative, this calculation neglects tailchase geometries (Region 7), which would lower the overall percentage if considered.

### 4.3.4 Probability of Adverse Maneuver

The potential fake-out scenarios identified in the previous section are only hazardous when the intruder executes an adverse maneuver during a limited interval of time. The next step in the analysis estimates the frequency for which this will occur. The Piedmont data does not contain any altitude-crossing Resolution Advisories, and contains only 3 altitude-crossing Traffic Advisories. Therefore, the estimate will be made from the dynamics of all traffic observed, with the possibility noted that this may not account for differences when the aircraft fly close together.

Figure 4-18 is a histogram giving a breakdown of all valid Piedmont tracks in three groups: "L" denotes always level, "R"

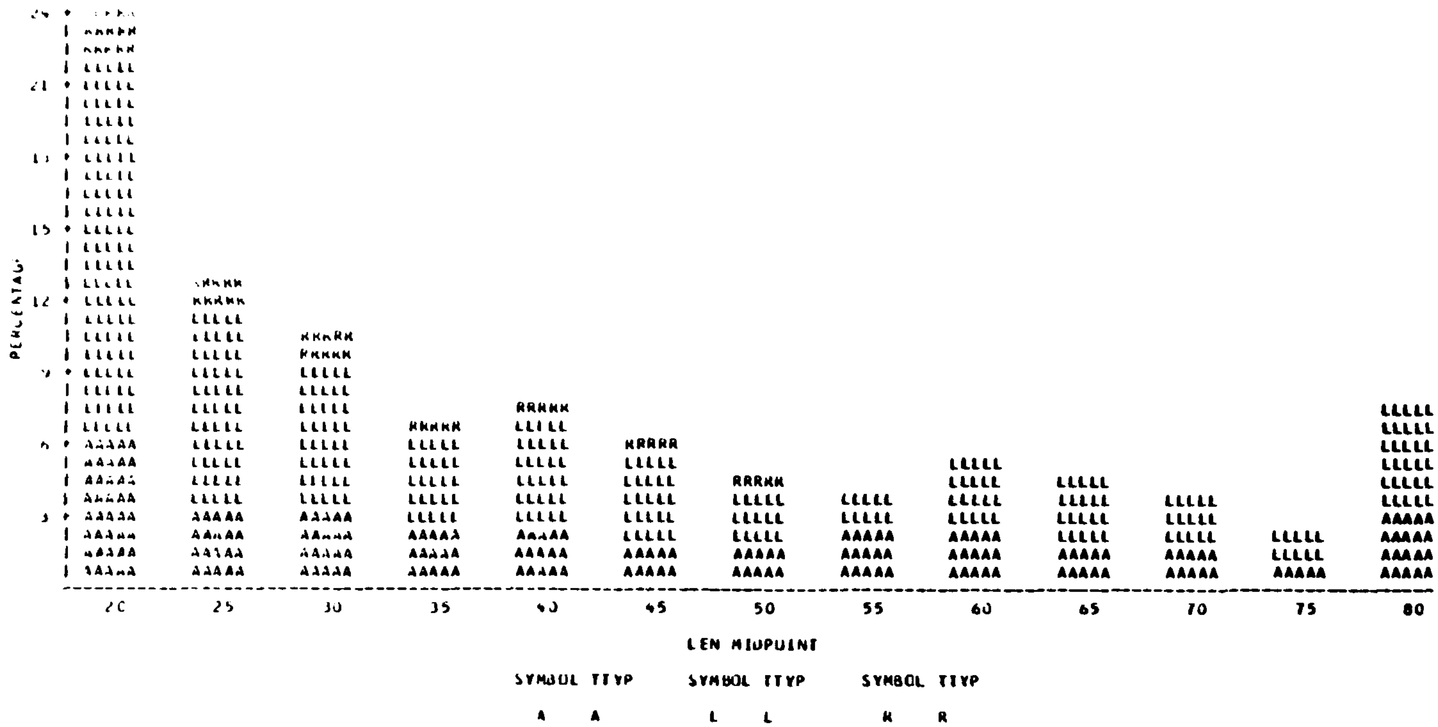



**FIGURE 4-18**
**PROBABILITY OF ACCELERATION HISTOGRAM**

denotes a constant vertical rate; "A" denotes a change in rate of 8 ft/sec or more. The tracks are tabulated by track length, since the probability of maneuver should increase over a longer time sample. It should be noted that the distribution of track lengths is mainly determined by the tape recording algorithm, and bears little relation to surveillance track lengths. Observe from this figure that accelerations form a high proportion of tracks with vertical rates (the ratio of A to (A+R)). Thus, ignoring the level tracks (L), accelerations are seen in 75 percent of the shorter tracks, and increase with track length to 100 percent (no long "R" tracks). This behavior suggests a Poisson probability distribution of the vertical acceleration "event", given an initial vertical rate. Since the longer tracks may contain more than one acceleration, which was not counted in the sampling program, the shorter tracks were used to evaluate the Poisson parameter. The resulting model is:

Prob. (acceleration in T seconds, given an initial rate)

$$= 1 - \exp(-.036\ T)$$

This formula is needed since for any level-off maneuver there is a specific time window causing the final altitude to be a potential NMAC (see Figure 4-19). For each vertical rate in Table 4-6, the time windows were calculated corresponding to: a) no maneuver before reaching the critical altitude; and b) a maneuver at the critical altitude, plus or minus 100 ft. These intervals and their probabilities from the Poisson model are also shown in Table 4-6. These are multiplied by the probability of the potential NMAC scenario to produce the

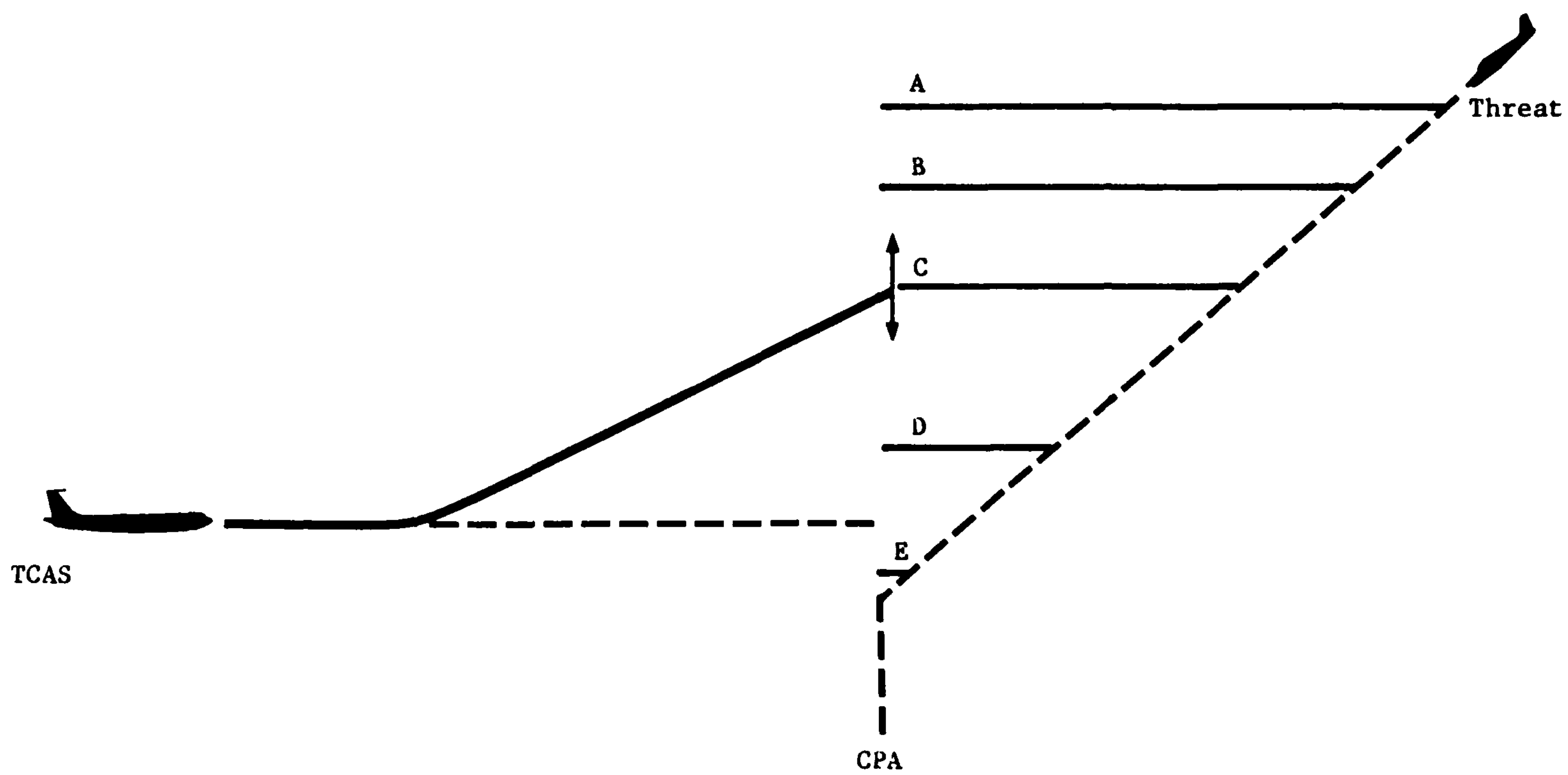



**FIGURE 4-19**
**EXAMPLE OF POTENTIAL FAKE-OUT SCENARIO**

probability of an NMAC in the last column. This column sums to .00270.

This result should serve as an upper bound to the actual NMAC figure for several reasons:

1. The calculation assumes that the maneuver is of the worst direction and magnitude, that is, level-off. Data shows that maneuvers may be in either direction. For Piedmont intruders (Advisories) with vertical rates (not necessarily in crossovers), 23 decreased their rate or reversed their direction; 17 increased their rate; and 4 maintained their rate. Of crossovers, 9 maneuvered to reinforce the crossover; 4 maneuvered to prevent the crossover; and 1 maneuvered both ways. Thus it is not indicated that all maneuvers are adverse.

2. For the case of TCAS-II equipped threats, an adverse maneuver should never occur, since both pilots receive coordinated Resolution Advisories.

3. The probability of intruder maneuver may be high by as much as a factor of 2. The "accelerating" tracks on the Piedmont tapes included level-to-rate accelerations as well as rate-to-level accelerations. These categories were not counted separately when the tapes were analyzed. If the proportions were consistent with the database used in the profile segment study (Section 3.3.3), the maneuver hazard would be half the value derived above.

### 4.3.5 Additional Observations

The analysis given above has been concerned with level-off maneuvers near TCAS' final altitude, i.e., about 500 ft away. For several reasons, a level-off maneuver 1000 ft from TCAS is much less likely to lead to an NMAC. First, the intruder must have a rate greater than 2000 fpm near the assigned altitude to induce this sense choice. (Table 3-7 indicates this probability is much less than 10 percent.) Second, the advisory time (TAU threshold) does not provide sufficient time for TCAS to displace 1000 ft with a standard maneuver. Third, the "Advisory Not-OK" indication should give the TCAS pilot more time to moderate or stop the wrong-way maneuver than in encounters with 500 ft separation. Thus, for flight in airspace where 1000 ft separation is the normal procedure (e.g. in IMC), the Risk Ratio caused by a maneuvering intruder is expected to decrease from about .003 by about two orders of magnitude.

Since any fake-out is a relatively abrupt maneuver, the Airman's Information Manual was examined for its procedure on following ATC clearances. This manual provides guidance only, and is used primarily by General Aviation pilots. The manual advises a pilot to reduce vertical rate to 500 fpm during the last 1000 ft of altitude transition to a new altitude clearance. If this procedure were followed by an intruder leveling 500 ft or more away from TCAS, the altitude-crossing sense would be even less frequent. It appears that fake-out maneuvers would be quite rare if most aircraft attempted to use this procedure.

In the event of a fake-out maneuver, TCAS gives the pilot an "Advisory Not-OK" display when tracker firmness regains high confidence, unless TCAS is projected to clear the threat by at least 100 feet. The time of such an advisory is greatly variable. For the case of a high initial rate and high acceleration, the pilot may receive 10 seconds warning. For lower rates or accelerations, very little warning time may be given. In any event, the Traffic Advisory is updated each second throughout the encounter to assist the pilot in monitoring intruder altitude and rate (using the rate arrow on the TA display). The analysis does not take credit for the benefits that may be ascribed to these features.

Finally, this study does not quantitatively evaluate the crosslink message sent by TCAS-II to TCAS-I. As with all Mode S communications, the physical link has a very high degree of integrity. The crosslink is intended to help the TCAS-I pilot visually acquire the TCAS II, and thereby assist in maintaining safe separation.

### 4.3.6 Summary of Effects of Maneuvering Intruders

The bound on a proximate maneuvering intruder inducing an NMAC was given as .0027. This can be roughly converted to Risk Ratio by multiplying the result by 10, because there are about 10 times as many proximate encounters as critical NMACs (as noted in Section 3). That is, if maneuvering intruder problems were the only failure mechanisms, TCAS would have a residue of about 2.7 percent of the present NMACs.

In Appendix C an estimate was made of the probability of a fake-out maneuver leading to an NMAC, using a different method and a different data base. This estimate was $5.70 \times 10^{-7}$, given a proximate encounter. To place those results on the same basis as the ones in this section, we merely remove the horizontal separation criterion from Table C-1 (.0005; an NMAC already has close horizontal proximity); then we apply the same times 10 vertical factor to relate it to the present NMACs. The result is $(5.70 \times 10^{-7} / .0005) \times 10 = .0114 = 1.1$ percent. The two estimates are quite close.

# 5. ANALYSIS OF PRINCIPAL TCAS FAILURE MECHANISMS

The preceding section treated external factors that could degrade the desired results of TCAS; this section analyzes internal factors. These factors are related to the surveillance function of TCAS, persistent bit errors in the intruder's reply of altitude, and various combinations of failures in the avionics of either aircraft.

## 5.1 Surveillance-related Faults

Imperfections in the tracks produced by the air-to-air surveillance subsystem of TCAS II can affect the information presented to the threat detection and resolution algorithms. The following sections classify the effects and mechanisms that are possible, and then provide estimates of the frequencies of occurrence.

### 5.1.1 Types of Surveillance Imperfections

There are four types of surveillance imperfections that may affect the system:

- Misses
- False tracks
- Location errors
- Track number changes

A miss is the event that an aircraft exists in the vicinity of the TCAS II-equipped aircraft, and yet there is no surveillance track corresponding to that aircraft at that time. Such an event can be caused by, for example, a fade in received power, which may in turn be caused by a dip in one or both of the antenna patterns. If the aircraft is near enough to cause an RA to be triggered, and if the track is missing during that whole time period, then the result will simply be that no advisory is produced. It is also possible for the track to start late, in which case the effect is a late advisory, leaving less time for pilot and aircraft reaction. The other possibility is that the track exists at the time the RA is triggered but is dropped later, which may cause the pilot display to go blank before the resolution is complete.

A false track is a track that does not correspond to any real aircraft. In Mode S surveillance, false tracks do not occur (because of the discrete addressed interrogations). In Mode C, however, false tracks are possible. The main mechanism causing false tracks in Mode C is multipath. Multipath connotes radio reflections from the ground or ocean over which the aircraft are flying. There are other mechanisms that can cause false tracks, and it is physically possible for an RA to be triggered by a false track at a time when there is no aircraft close enough to trigger an RA. In the event that a false track is within the threat volume at a time when an aircraft is also within the threat volume, the false track may have the effect of modifying the displayed RA relative to what would have been displayed in the absence of the false track. The other possibility is that a false track and a real track are both within the threat volume at the same time, and yet the displayed RA is not changed in any way by the presence of the false track.

Location errors in both range and altitude have been noted occasionally in TCAS surveillance data and could conceivably have some effect on RAs. A location error is a condition in which a track exists, corresponding to an aircraft in the vicinity, but the tracked location differs from the location of the aircraft by an amount that is large relative to normal surveillance accuracy. Location errors in range may be a result of multipath acting in combination with direct replies. In a case where both multipath replies and direct replies are being received and both are intermittent, the track may oscillate back and forth between the two types of replies, thus causing range deviations. Location errors in altitude may result from bit declaration errors in the demodulation of the received altitude code.

Ordinarily the track number of a surveillance track is a constant for the duration of an encounter. This information is used by the threat logic in the functions that estimate range rate and altitude rate; the rate estimates for a given track are derived only from data tagged with the track number. Track number changes have occasionally been observed in TCAS surveillance data, and thus some effect on RAs could conceivably result. A track number change may occur in a case of crossing tracks. Here, two tracks cross in range (which is very common) while they are at the same altitude (which is less likely). The two corresponding aircraft need not be close to each other; they are more likely far apart in azimuth. Crossing tracks are somewhat rare, and in most cases the track numbers remain correct throughout, but it is possible for these to swap.

### 5.1.2 Frequency of Occurrence

For each of the identified surveillance imperfections, an estimate was obtained of the frequency of occurrence. Data sets that are appropriate for this purpose were obtained by flights with special instrumentation directed to the collection of surveillance data. These are:

1. Airborne data recorded during 1983 subject pilot testing at Lincoln Laboratory. These flights were in a Cessna 421. A TCAS Experimental Unit (TEU) was used.

2. Airborne data recorded during the 1982 high density test program. Some of this data is recorded in the Los Angeles basin and some was recorded on the East Coast. These flights were in a Boeing 727. A TEU was used.

While the Piedmont Phase I data is useful in identifying mechanisms that may occur, this data set and all other data sets obtained using BCAS air-to-air surveillance will not be used here because of the significant changes between the earlier BCAS and the TCAS II equipment. For example, the change from 4-level whisper-shout in BCAS to 24-level whisper-shout in TCAS II was intended to reduce the frequency of occurrence of misses in high density airspace, and may also be expected to affect the false track rate.

A straightforward way of assessing frequencies of occurrence is to examine all cases in which an RA was generated and note the fraction of cases in which each type of imperfection occurred. To date this has been carried out for 65 RA encounters from data set (1). In 61 of the encounters, surveillance imperfections had no effect on displayed RAs. In three of the encounters the track was dropped near the point of closest approach. In each such case the track drop was preceded by a substantial period during which the nominal RA was displayed (29, 40, and 54 seconds). In the remaining encounter, an altitude error of 100 ft occurred just as RA sense was being selected. This converted "descend" into "climb." The pilot considered this to be the wrong way, although the climb advisory would have provided adequate vertical separation at CPA. The version of threat logic that was used in this flight was, however, significantly different in its reaction to this condition relative to the threat logic in its current form. The current form of threat logic would have reacted with a "descend" RA. Thus for the entire set of 65 encounters analyzed, in no case did the surveillance data cause an incorrect RA (based on the current form of threat logic).

These results are encouraging. Although they do not provide detailed estimates of frequencies of occurrence, they do indicate that the values are small.

Less straightforward ways of analyzing airborne data may be useful in obtaining rate estimates by extrapolation. A study has been conducted of the Los Angeles basin portion of data set (2) to estimate the miss rate for closing rates of 500 knots in high density airspace. Although there were no 500 knot encounters in the data, the study was done by focusing on the range at which surveillance would be required for a 500 knot encounter, about 4.5 nmi. The result for the probability of having the aircraft in track early enough to trigger the RA, including a portion of lead-in track to provide for accurate estimates of range rate and altitude rate, is 95 percent.

This is a conditional probability, based on the following:

- Flying in airspace of high aircraft density
- Closing rate of 500 knots

The more typical, or unconditional, performance is expected to be somewhat better, about 97 percent. Likewise, the typical probability of having the aircraft in track at the time of the TA is 94 percent. Stated differently, the probability of not having the aircraft in track by the time of the TA is .06, and by the time of the RA is .03.

Quantitative estimates of the frequencies of occurrence in the other three categories must be arrived at through judgments based on experience with airborne data which includes BCAS data. An estimate of the rate of false tracks is less than 3 percent. (*From a study of airborne* flight data, occasional brief false tracks occurred at a rate of 1.1 percent for the directional system and 1.9 percent for the omnidirectional system.) That is, among all RA encounters less than 3 percent will be affected by a false track. In the majority of these cases (perhaps 9 out of 10) the modified RA will still provide for separation from the aircraft causing the RA and will be safe. Location errors and track number changes that affect RAs are believed to be less frequent. A value of 1 percent can be taken as a pessimistic estimate of the frequency of occurrence of both classes together. Again, when these effects occur they typically result in an RA that provides for separation from the aircraft in the vicinity.

## 5.2 Mode C Bit Failure

TCAS uses transponded Mode C data, updated once a second, obtained from the aircraft under surveillance to determine its altitude. Errors in encoding the altitude will introduce errors in subsequent results.

This section will investigate the impact of a persistent encoder bit failure on TCAS resolution performance. Particular emphasis will be placed on errors which will cause TCAS to create a hazardous situation. Using recorded surveillance data collected on TCAS test flights and at the NASA facility at Wallops Island, Virginia, empirical estimates of the occurrence of Mode C bit errors are made.

### 5.2.1 Mode C Altitude Encoding and C-Bit Errors

The ability of TCAS to accurately track aircraft in the vertical dimension is dependent upon consistent and accurate Mode C data. This information is encoded by a transponder and transmitted in Gilham code, often referred to as modified Gray code. Modified Gray code has the property that only one bit changes between the representation of any two adjacent altitude levels. The code is represented by 12 bits or pulses transmitted from left to right as follows:

C1 A1 C2 A2 C4 A4 B1 D1 B2 D2 B4 D4

The D1 bit is not used for altitude encoding. The eight bits which occupy pulse positions D2, D4, A1, A2, A4, B1, B2, and B4, encode the altitude in 500 ft stages. By the addition of another three pulses C1, C2, and C4, which represent another cyclic binary code, fine coding in 100 ft intervals is achieved.

Errors in the tracked aircraft's altitude track can be due to several causes; this section will deal only with the "stuck bit" error problem in the low order bits (the C pulses). The C bits cycle the most rapidly, identifying the aircraft's 100 ft level within each 500 ft altitude bin, defined by the high order bits. Errors in the higher order bits result in large errors (500 ft or larger) and will normally be detected by ATC, which will direct that the Mode C of the malfunctioning transponder be turned off. Also, for any threat with a high order bit error, the resulting large jumps in reported altitude will be rejected by the TCAS altitude credibility test. Errors in the low order bits, however, may go undetected by ATC, and, although those errors do not produce large differences between reported and true flight levels, they can produce significant errors in the position projections performed by TCAS.

### 5.2.2 Properties of C-Bit Errors

A Karnaugh map representation of the C-bit coding is provided in Table 5-1. Although there are eight possible states for the 3 C-bits, only five of these states are used. The remaining three unused states are referred to as illegal states. They correspond to C1 C2 C4 = 000, 101, and 111. Each 1000 foot altitude interval contains the same sequence of C-bits. Higher order bits change between altitude levels which end in 200-300 and 700-800.

Table 5-2 provides a description of the possible single-bit errors in the C-bits. Bit errors of +C1, +C2, +C4 refer to the C1, C2, or C4 bits, respectively, always set to one; -C1, -C2, -C4 denote the same bits always set to zero. When the subject bit should have the opposite value, a bit error results. The next ten columns in Table 5-2 show the sequence of altitudes

TABLE 5-1
KARNAUGH MAP OF C-BIT VALUES

| C1 \ C2 C4 | 00 | 01 | 11 | 10 |
|---|---|---|---|---|
| 0 | X | 8,7 | 9,6 | 0,5 |
| 1 | 2,3 | X | X | 1,4 |

Karnaugh Map showing correspondence of C-bit values with last digit of 100-foot altitude level. The three illegal states are indicated by X.

TABLE 5-2
RESULTS OF SINGLE-BIT ERRORS IN C-BITS

| BIT ERROR | SEQUENCE (Last digit of 100 feet level) 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | DISCONTINUITY | NO. MISSING LEVELS | NO. ILLEGAL STATES | NO. LEGAL ERRORS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -C1 | 0 | 0 | X | X | 5 | 5 | 6 | 7 | 8 | 9 | 500 | 4 | 2 | 2 |
| +C1 | 1 | 1 | 2 | 3 | 4 | 4 | X | X | X | X | 700 | 5 | 4 | 2 |
| -C2 | X | 2 | 2 | 3 | 3 | X | 7 | 7 | 8 | 8 | 400 | 5 | 2 | 4 |
| +C2 | 0 | 1 | 1 | 4 | 4 | 5 | 6 | 6 | 9 | 9 | 300 | 4 | 0 | 4 |
| -C4 | 0 | 1 | 2 | 3 | 4 | 5 | 5 | X | X | 0 | 500 | 4 | 2 | 2 |
| +C4 | 9 | X | X | X | X | 6 | 6 | 7 | 8 | 9 | 700 | 6 | 4 | 2 |

that result in the 100 ft altitude bins. For example, for a -C1 error (no C1 pulse), 500 ft will be encoded when an aircraft is at the 400 ft bin. An "X" indicates the bit error results in an illegal state at that altitude bin. Note that reported altitudes increase monotonically with increasing actual altitude.

The table also shows discontinuities in altitude bins represented; these are gaps between legally occurring states. For example, a 400 ft discontinuity occurs for an aircraft transitioning from the 400 ft bin to 600 ft bin when there is a -C2 bit error (missing C2 pulse). The Mode C reply shows 300 ft when the aircraft is at 400 ft, then shows an illegal state, then shows 700 ft when the aircraft is at 600 ft. Thus, a jump of 400 ft between consecutive legal Mode C replies occurs when only 200 ft have been transited. The table also shows the number of missing levels (altitude bins which will never be encoded for that error type), number of illegal states, and number of bins which will be encoded incorrectly. Table 5-3 shows the differences between the altitude level intended and the altitude level actually encoded. A "-1" indicates an altitude will be shown which is 100 ft below the correct altitude; a "+1" indicates that an altitude will be shown which is 100 ft above the correct altitude. There is no C-bit error which will result in greater than 100 ft error in represented altitude.

It is seen that the only error type which results in a discontinuity between adjacent actual altitude levels (that is, with no illegal state within the discontinuity) is +C2. For this error, the encoded value jumps from a level ending in 100 to a level ending in 400 when the actual level transition is

TABLE 5-3
ERRORS (x 100 ft) ASSOCIATED WITH GIVEN C-BIT ERROR

| BIT ERROR \ SEQUENCE NUMBER | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| -C1 | 0 | -1 | X | X | +1 | 0 | 0 | 0 | 0 | 0 |
| +C1 | +1 | 0 | 0 | 0 | 0 | -1 | X | X | X | X |
| -C2 | X | +1 | 0 | 0 | -1 | X | +1 | 0 | 0 | -1 |
| +C2 | 0 | 0 | -1 | +1 | 0 | 0 | 0 | -1 | +1 | 0 |
| -C4 | 0 | 0 | 0 | 0 | 0 | 0 | -1 | X | X | +1 |
| +C4 | -1 | X | X | X | X | +1 | 0 | 0 | 0 | 0 |

X = Illegal Code Reported

-Ci = Ci bit always set to zero

+Ci = Ci bit always set to one

200 to 300. For error types other than +C2, discontinuities between encoded altitudes contain illegal states between the legally encoded levels. The discontinuities for these error types may be 400, 500 or 700 feet.

It is possible to use Table 5-2 to determine the type of bit error which may be responsible for a particular reporting anomaly. For instance, suppose that when sequence number 0 was expected, sequence number 1 occurred. From Table 5-2 it is seen that a +C1 error is the only single-bit C-bit error which could produce this conversion. By tabulating the types of C-bit conversions which occur for an observed track, the nature of any persistent single-bit C-bit errors can be deduced.

### 5.2.3 Impacts of C-Bit Errors on TCAS Performance

In examining TCAS data it should be kept in mind that altitude discontinuities of more than 300 feet may result in track coast or track termination. Reporting of an illegal altitude will also result in track coast. If reporting of an illegal altitude is persistent, then the aircraft may be tracked as a non-Mode C aircraft. In order to fully evaluate bit errors, it is desirable to obtain from the surveillance software the actual decoded altitude of each reply or the specific type of illegal reply received.

The primary concern with C-bit errors is their impact on TCAS' ability to maintain track and to track accurately, such that the collision avoidance function is not impaired. C-bit errors have little impact on TCAS' ability to perform its role of collision avoidance when the aircraft with the "stuck bit" is in level flight. The impact of a C-bit error on the TCAS tracking of an aircraft in level flight is dependent upon the assigned flight level and the adherence of the aircraft to the assigned altitude. Normally, aircraft are assigned altitudes ending in 000 if IFR and 500 if VFR. Tables 5-4 and 5-5 show the impact of C-bit errors on transponded altitude for aircraft assigned to these flight levels. The second and third columns in each table show the percentage and magnitude of deviations from assigned flight levels typically encountered, the percentages are taken from Reference 33. Note that the impact of C-bit errors can easily be computed for any assigned flight level by shifting columns 2 and 3 to the desired true altitude and summing the proportions in column 3 over each condition in the C-bit error columns (0=good report, 1=report in error by 100 feet, X=coast received). In this way, allowance could be made for nonstandard pressure, where an assigned flight level corresponds to a different transponded altitude. Since aircraft transponded altitudes are always determined relative to standard pressure, this analysis pertains only to C-bit induced tracking problems. It is assumed that the frequency of deviations about an assigned altitude is not any larger at the lower altitudes; however, for a worst case condition Table 5-6 presents the impact of C-bit errors on level flight tracking, assuming deviations follow a uniform distribution. It is assumed that the frequency of deviations will not be any larger at the lower altitudes. The distribution does not account for the time correlation of successive deviations.

Although tracking level aircraft with C-bit errors poses no problem with the TCAS tracking algorithm, there is the strong possibility that a Mode C track would not be formed for aircraft with a persistent error in the C2 bit. A -C2 bit error and +C2 bit error, depending on assigned altitude (000 or 500), would result in a coast approximately 71 percent of the

TABLE 5-4

IMPACT OF C-BIT ERRORS: LEVEL FLIGHT - 1000' ASSIGNED ALTITUDE

| TRUE ALTITUDE | DEVIATIONS FROM LEVEL FLIGHT | PROPORTION OF TIME DEVIATIONS OCCUR | TRANSPONDED ALTITUDES GIVEN C-BIT ERRORS -C1 | | +C1 | | -C2 | | +C2 | | -C4 | | +C4 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| xx400 | +400 | $1.9 \times 10^{-4}$ | +500 | 1 | xx400 | 0 | xx300 | 1 | xx400 | 0 | xx400 | 0 | COAST | X |
| xx300 | +300 | $1.26 \times 10^{-3}$ | COAST | X | xx300 | 0 | xx300 | 0 | xx400 | 1 | xx300 | 0 | COAST | X |
| xx200 | +200 | $1.1 \times 10^{-2}$ | COAST | X | xx200 | 0 | xx200 | 0 | xx100 | 1 | xx200 | 0 | COAST | X |
| xx100 | +100 | .13 | xx000 | 1 | xx100 | 0 | xx200 | 1 | xx100 | 0 | xx100 | 0 | COAST | X |
| xx000 | 0 | .71 | xx000 | 0 | xx100 | 1 | COAST | X | xx000 | 0 | xx000 | 0 | xx900 | 1 |
| xx900 | -100 | .13 | xx000 | 0 | COAST | X | xx800 | 1 | xx900 | 0 | xx000 | 1 | xx900 | 0 |
| xx800 | -200 | $1.0 \times 10^{-2}$ | xx800 | 0 | COAST | X | xx800 | 0 | xx900 | 1 | COAST | X | xx800 | 0 |
| xx700 | -300 | $6.7 \times 10^{-4}$ | xx700 | 0 | COAST | X | xx700 | 0 | xx600 | 1 | COAST | X | xx700 | 0 |
| xx600 | -400 | $1.2 \times 10^{-4}$ | xx600 | 0 | COAST | X | xx700 | 1 | xx600 | 0 | COAST | 1 | xx600 | 0 |
| | | | | | | | | | | | | | | |
| % of time GOOD REPORTS RECEIVED | | (0) | 85.25 | | 14.24 | | 2.29 | | 97.03 | | 85.25 | | 14.08 | |
| % of time REPORTS IN ERROR BY 100' | | (1) | 13.02 | | 71.00 | | 26.03 | | 2.29 | | 13.01 | | 71.00 | |
| % of time COAST RECEIVED | | (X) | 1.23 | | 14.08 | | 71.00 | | 0 | | 1.07 | | 14.25 | |

TABLE 5-5

IMPACT OF C-BIT ERRORS: LEVEL FLIGHT - 500' ASSIGNED ALTITUDE

| TRUE ALTITUDE | DEVIATIONS FROM LEVEL *FLIGHT* | PROPORTION OF TIME *DEVIATIONS* OCCUR | TRANSPONDED ALTITUDES GIVEN C-BIT ERRORS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | −C1 | | +C1 | | −C2 | | +C2 | | −C4 | | +C4 | |
| xx900 | +400 | $1.9\times10^{-4}$ | xx900 | 0 | COAST | X | xx800 | 1 | xx900 | 0 | xx000 | 1 | xx900 | 0 |
| xx800 | +300 | $1.26\times10^{-3}$ | xx800 | 0 | COAST | X | xx800 | 0 | xx900 | 1 | COAST | X | xx700 | 0 |
| xx700 | +200 | $1.1\times10^{-2}$ | xx700 | 0 | COAST | X | xx700 | 0 | xx600 | 1 | COAST | X | xx600 | 0 |
| xx600 | +100 | .13 | xx600 | 0 | COAST | X | xx700 | 1 | xx600 | 0 | xx500 | 1 | xx600 | 0 |
| xx500 | 0 | .71 | xx500 | 0 | xx400 | 1 | COAST | X | xx500 | 0 | xx500 | 0 | xx600 | 1 |
| xx400 | −100 | .13 | xx500 | 1 | xx400 | 0 | xx300 | 1 | xx400 | 0 | xx000 | 1 | COAST | X |
| xx300 | −200 | $1.0\times10^{-2}$ | COAST | X | xx300 | 0 | xx300 | 0 | xx400 | 1 | COAST | X | COAST | X |
| xx200 | −300 | $6.7\times10^{-4}$ | COAST | X | xx200 | 0 | xx200 | 0 | xx100 | 1 | COAST | X | COAST | X |
| xx100 | −400 | $1.2\times10^{-4}$ | xx000 | 1 | xx100 | 0 | xx200 | 1 | xx100 | 0 | COAST | 1 | COAST | X |
| % of time GOOD REPORTS RECEIVED | | (0) | 85.25 | | 14.08 | | 2.29 | | 97.03 | | 85.25 | | 14.24 | |
| % of time REPORTS IN ERROR BY 100' | | (1) | 13.02 | | 71.00 | | 26.03 | | 2.29 | | 13.02 | | 71.00 | |
| % of time COAST RECEIVED | | (X) | 1.07 | | 14.25 | | 71.00 | | 0 | | 1.23 | | 14.08 | |

TABLE 5-6

IMPACT OF C-BIT ERRORS: LEVEL FLIGHT - UNIFORM DEVIATION

| TRUE ALTITUDE | DEVIATIONS FROM ASSIGNED FLIGHT LEVEL | PROPORTION OF TIME DEVIATIONS OCCUR | TRANSPONDED ALTITUDES GIVEN C-BIT ERRORS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | -C1 | | +C1 | | -C2 | | +C2 | | -C4 | | +C4 | |
| xx400 | +400 | .11 | +500 | 1 | xx400 | 0 | xx300 | 1 | xx400 | 0 | xx400 | 0 | COAST | X |
| xx300 | +300 | .11 | COAST | X | xx300 | 0 | xx300 | 0 | xx400 | 1 | xx300 | 0 | COAST | X |
| xx200 | +200 | .11 | COAST | X | xx200 | 0 | xx200 | 0 | xx100 | 1 | xx200 | 0 | COAST | X |
| xx100 | +100 | .11 | xx000 | 1 | xx100 | 0 | xx200 | 1 | xx100 | 0 | xx100 | 0 | COAST | X |
| xx000 | 0 | .11 | xx000 | 0 | xx100 | 1 | COAST | X | xx000 | 0 | xx000 | 0 | xx900 | 1 |
| xx900 | -100 | .11 | xx000 | 0 | COAST | X | xx800 | 1 | xx900 | 0 | xx000 | 1 | xx900 | 0 |
| xx800 | -200 | .11 | xx800 | 0 | COAST | X | xx800 | 0 | xx900 | 1 | COAST | X | xx800 | 0 |
| xx700 | -300 | .11 | xx700 | 0 | COAST | X | xx700 | 0 | xx600 | 1 | COAST | X | xx700 | 0 |
| xx600 | -400 | .11 | xx600 | 0 | COAST | X | xx700 | 1 | xx600 | 0 | COAST | 1 | xx600 | 0 |
| % of time GOOD REPORTS RECEIVED | | (0) | 55.55 | | 44.44 | | 44.44 | | 55.55 | | 55.55 | | 44.44 | |
| % of time REPORTS IN ERROR BY 100' | | (1) | 22.22 | | 11.11 | | 44.44 | | 44.44 | | 22.22 | | 11.11 | |
| % of time COAST RECEIVED | | (X) | 22.22 | | 44.44 | | 11.11 | | 0 | | 22.22 | | 44.44 | |

time since the assigned altitude is an illegal code for these C-bit errors. These tracks would then be designated as "altitude unknown."

Aircraft which have a stuck C bit and which have vertical rates do pose a tracking problem for the TCAS tracking algorithm. This problem cannot be remedied by a simple algorithm modification. Figure 5-1 shows the impact on tracking that would occur for an aircraft at various vertical rates with a -C2 bit error. Only scans with "firmness" value greater than or equal to 2 were used since sense selection is made only with these values. The magnitude of the projection errors varies with aircraft rate and type of error; however, the central theme is that the projection errors can be large in the presence of C-bit errors.

A simulation model was used to estimate the impact of C-bit errors on vertical rate projections by TCAS. Aircraft were simulated and tracked with vertical rates of 500 fpm, 2000 fpm, 4000 fpm, and the six types of bit errors. The number of observations for which the track retained high firmness were counted. Using the nominal 30 second projection employed by the collision avoidance logic, the magnitude of the errors associated with a given C-bit error were counted to determine the percentage which were in excess of 300 ft. In Table 5-7 the results are given for the three vertical rates. The two columns under each vertical rate represent the proportion of time the rate estimate was considered adequate for resolution (firmness greater than or equal to 2) and the percentage of time the error in the rate estimate would cause the vertical projection error to exceed the anticipated maneuver displacement of TCAS. For example, given a +C2 bit error and a

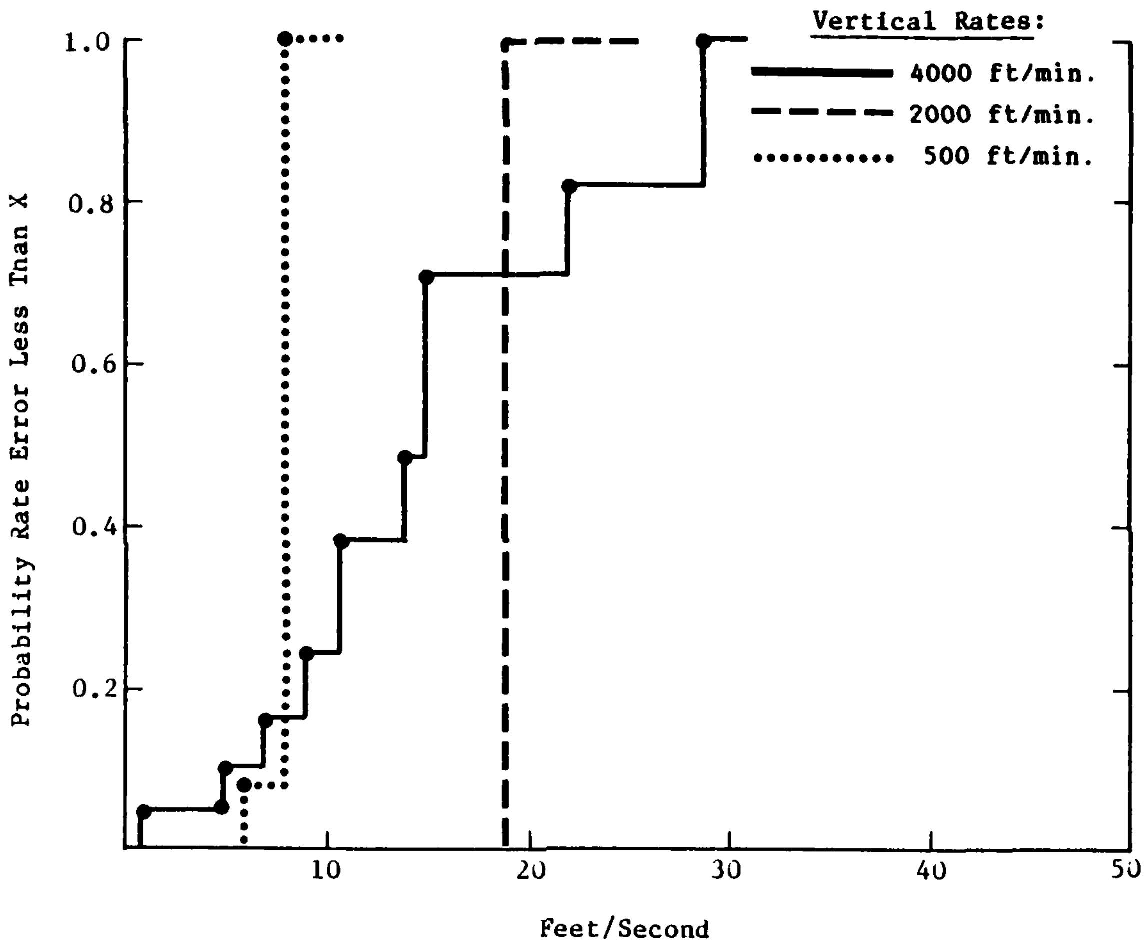



**FIGURE 5-1**
**PROJECTION RATE ERRORS WITH**
**-C2 BIT ERROR**

TABLE 5-7
IMPACT OF C-BIT ERRORS ON PROJECTED VERTICAL POSITION

| C-BIT ERROR \ VERTICAL RATE | 500 FEET/MINUTE | | 2000 FEET/MINUTE | | 4000 FEET/MINUTE | |
|---|---|---|---|---|---|---|
| | PERCENTAGE OBSERVATIONS ACCEPTED | PERCENTAGE RESULTING IN PROJECTED ERROR GREATER THAN MANEUVER | PERCENTAGE OBSERVATIONS ACCEPTED | PERCENTAGE RESULTING IN PROJECTED ERROR GREATER THAN MANEUVER | PERCENTAGE OBSERVATIONS ACCEPTED | PERCENTAGE RESULTING IN PROJECTED ERROR GREATER THAN MANEUVER |
| -C1 | 70% | 14% | 50% | 20% | 60% | 0% |
| +C1 | 50% | 60% | 24% | 0% | 41% | 85% |
| -C2 | 50% | 100% | 40% | 100% | 40% | 75% |
| +C2 | 55% | 27% | 20% | 100% | 45% | 44% |
| -C4 | 70% | 14% | 50% | 20% | 60% | 25% |
| +C4 | 50% | 0% | 21% | 0% | 50% | 54% |
| Probability of Projection Error Exceeding Displacement | .191 | | .133 | | .211 | |

ANTICIPATED MANEUVER DISPLACEMENT = 300 ft

500 ft per minute vertical rate, 55 percent of the time the rate estimate would have been declared adequate for sense selection. For these cases, where it was adequate for sense selection, 27 percent of the time the projection error would have exceeded 300 feet. Overall, 15 percent (27 percent X 55 percent) of the time the vertical projection error would have exceeded 300 feet. Assuming all C-bit errors are equally likely, the overall probability of C-bit errors causing the vertical projection error to exceed 300 ft is also presented on Table 5-7.

The illegal codes resulting from C-bit errors would also affect the ability of TCAS to maintain track continuity on aircraft with vertical tracks. The actual sequence of track drops and reinitializations of the same track are dependent upon the aircraft vertical rate, coast count required to drop track, number of reports required to initiate a track, and type of C-bit error present. Low vertical rates would obviously result in longer coast periods since the aircraft would be in altitude bins which result in illegal codes for longer periods of time. Table 5-8 shows the vertical rates below which a specified number of illegal codes (resulting in coasts) occur.

### 5.2.4 Frequency of C-Bit Errors

Since the problem of C-bit errors can adversely affect the TCAS role of collision avoidance, an effort was made to estimate how frequently C-bit errors occur.

In order to detect C-bit errors it is necessary to examine the Mode C patterns of vertical tracks and match with Mode C patterns representative of the various C-bit errors as shown in Table 5-3. The reliability of this method is dependent upon

TABLE 5-8
MAXIMUM VERTICAL RATES RESULTING IN SPECIFIED COAST PERIODS

| | VERTICAL RATE (ft/min) BELOW WHICH SPECIFIED CONSECUTIVE COASTS OCCUR | | | | | |
|---|---|---|---|---|---|---|
| CONSECUTIVE COASTS | -C1 | +C1 | -C2 | +C2 | -C4 | +C4 |
| 6 | 2000 | 4000 | 1000 | NO ILLEGAL CODES | 2000 | 4000 |
| 8 | 1500 | 3000 | 750 | " | 1500 | 3000 |
| 10 | 1200 | 2400 | 600 | " | 1200 | 2400 |
| 12 | 1000 | 2000 | 500 | " | 1000 | 2000 |

the number of 100 ft levels visited by the aircraft (altitude change), the number of Mode C observations at each level (vertical rate), and the ability to determine the correct Mode C reply (known true position of the aircraft). Therefore, it is desirable to examine vertical profiles which visit all 100 ft levels and have a high Mode C update rate to ensure data is collected on all 100 ft levels visited by the aircraft. It is also desirable to have a reference altitude profile for accurate determination of the true Mode C pattern. It should be noted that any analysis of track data for C-bit errors is influenced by the surveillance mechanism used in the data collection in terms of the sampling rate and surveillance induced errors such as synchronous garble and multipath.

The occurrence of C-bit errors has been detected by Gent through the dynamic monitoring of SSR Mode C data in England (Reference 34). Gent found persistent Mode C errors due to the addition or deletion of a single C bit either "simply" or "conditionally". By the term "conditionally", Gent means that in certain cases the presence or absence of a C-bit pulse is dependent upon the presence or absence of another pulse. Gent concluded that there was a persistent error rate of 1.8 percent for aircraft on approach and .7 percent for aircraft on departure. It should also be noted that Lincoln Laboratory has found Mode C patterns indicative of C-bit errors during flight tests; however, no attempt was made to determine the frequency of occurrence.

Gent's analysis was conducted under certain limitations. The SSR has a rotation of 10.8 rpm, which corresponds to 1 flight level Mode C update for a vertical rate of 1080 ft/min. For vertical rates above 1080 ft/min, Mode C data could not be collected on every 100 ft level visited by the aircraft. Gent did not have precision data on the true aircraft track and relied on inspection to determine the true Mode C pattern. The lack of persistent C-bit errors (range dependent from the radar) and the nature of "conditional" C-bit errors in Gent's analysis lead to questions concerning the possibility of multipath influencing some of the results. Multipath occurs when there is an overlap of replies in the bit pattern because of reflection from the ground or other structure.

The FAA Technical Center has undertaken a brief study of C-bit errors to determine their frequency of occurrence. This overcomes some of the foregoing limitations of Gent's study. The FAA Technical Center work is based on the analysis of existing TCAS flight test data and on Mode C data versus precision track data collected by the NASA/Wallops Flight Facility.

Although TCAS flight test data provides a 1 second update of Mode C data, the track duration is short (less than 110 seconds). Of 428 vertical tracks (46,600 track seconds), only 2 tracks were classified as having a probable C-bit error. In one case (-C4 bit) 14 out of an expected 16 bin reports were missing. In the other case (+C2 bit) 18 out of an expected 22 bin reports were missing.

The NASA/Wallops effort has yielded approximately 270 tracks for analysis. Preliminary analysis indicates no anomalies in the 100 ft altitude patterns of vertical tracks. One high order bit error in one track was detected. ATC observed this anomaly and subsequently had the aircraft pilot turn off the Mode C. The NASA/Wallops data has been collected, and the data is being analyzed.

Based on analysis of surveillance data collected during TCAS flights and preliminary analysis of Wallops Island data, the percentage of aircraft exhibiting Mode C bit errors is significantly smaller than the 2 percent postulated by Dr. Gent. Review of the surveillance data resulted in the detection of at most 2 transponders (0.47 percent) exhibiting Mode C bit error characteristics. A statistical confidence level can be computed to account for the finite sample size of this measurement. Using a 95 percent confidence level, the upper bound on the fraction of aircraft exhibiting a C-bit error is 1.2 percent; for 99 percent confidence, it is 1.3 percent. Preliminary analysis of the Wallops Island data detected only one failure condition (0.36 percent), and that was a higher order bit.

### 5.2.5 Conclusions on Risk Ratio for C-Bit Errors

Using the results of the transponder bit error analysis, conclusions about the probability of TCAS creating a hazardous situation due to encoder bit failure can be made. In addition to a proximate encounter, the following factors apply: (1) the intruding aircraft must have a vertical rate, (2) the intruding aircraft's transponder must have a C-bit failure, (3) the error in the projected vertical position caused by the encoder failure must be of sufficient magnitude, (4) the direction of the error in the projected vertical position must be detrimental to TCAS. Given that a proximate encounter condition exists, Table 5-9 presents the probability that a transponder bit failure would cause TCAS to create a hazardous situation. In Section 4.1 it was shown that proximate encounters occur approximately 10 times as frequently as an NMAC. Thus the nominal Risk Ratio ascribable to a bit failure is about .002.

TABLE 5-9
PROBABILITY OF C-BIT FAILURE CAUSING TCAS TO CREATE A HAZARDOUS SITUATION GIVEN A PROXIMATE CONDITION EXISTS

| EVENT | PROBABILITY |
|---|---|
| Intruder is not in level flight | 0.40 |
| Aircraft transponder has C-bit error | 0.005 Piedmont data<br>0.012 Upper bound of Wallops data (95% conf.) |
| C-bit error will cause at least a 300 foot error in projected vertical position | 0.20 |
| Error is in direction detrimental to TCAS | 0.50 |
| Probability of Events | $2.0 \times 10^{-4}$<br>$4.8 \times 10^{-4}$ (upper bound) |

Although higher order bit errors could prevent TCAS from alarming in a true threat situation, the higher order bit failure would not cause TCAS to create a hazardous situation. B-bit and higher order bits would cause large errors, which could easily be detected by ATC. Except for B4 bit failures, the higher order bits would cause such large bias in relative altitude that TCAS could not maneuver into the airspace occupied by the aircraft. B-bit failures for aircraft with vertical rates would cause large jumps in altitude resulting in surveillance coasting. This would result in a high fraction of low confidence rate estimates, which cannot be used in sense selection.

Lower order (C-bit) failures could lead to TCAS creating a hazardous situation. C-bit failures for aircraft with vertical rates could adversely affect the ability of the TCAS tracker to accurately predict position, thereby resulting in potential sense selection and command magnitude errors. C-bit failures for aircraft in level flight result in at most a 100 foot translation in the transponded Mode C altitude. This fact in itself would cause no problem for TCAS. Certain types of C bit errors (especially -C2) would cause an increase in the coast rates for intruders at the standard level flight altitudes. The probability of missed RA for an NMAC encounter is presented in Table 5-10. This calculation assumes all C-bit errors are equally likely. Depending on the details of the TCAS implementation, TCAS might still give the pilot an "altitude unknown" Traffic Advisory for this case.

TABLE 5-10
PROBABILITY OF C-BIT FAILURE CAUSING
MISSED RA, GIVEN NMAC ENCOUNTER

| EVENT | PROBABILTIY |
|---|---|
| Intruder is in level flight | 0.6 |
| Aircraft transponder has C-Bit error | 0.005 |
| C-Bit error causes TCAS surveillance to coast altitude reports | 0.166 |
| Combined Probability | $5.0 \times 10^{-4}$ |

## 5.3 Equipment Failure

Equipment failure may impact either of the two principal types of TCAS failures discussed in this report. The first is failure to resolve an NMAC. Any reasonably reliable equipment will have no appreciable effect on this probability.

The second type is the induced NMAC. The principal concern is a specific equipment failure that causes an incorrect RA, which together with a specific geometrical arrangement of the aircraft could lead to an NMAC. In Section 4, it was found that altimetry errors resulted in a Risk Ratio of about $10^{-2}$; the preceding section showed bit errors result in a Risk Ratio near $10^{-3}$. In order for equipment failure not to contribute significantly to induced NMACs, this cause of incorrect RA should be on the order of $10^{-4}$ per present NMAC.

Only some failures can lead to an incorrect RA (see Appendix F), and only some of these would go undetected by the TCAS Performance Monitor. Thus, a combination of reliable equipment, periodic maintenance, and Performance Monitoring all influence the rate of undetected failures of this type.

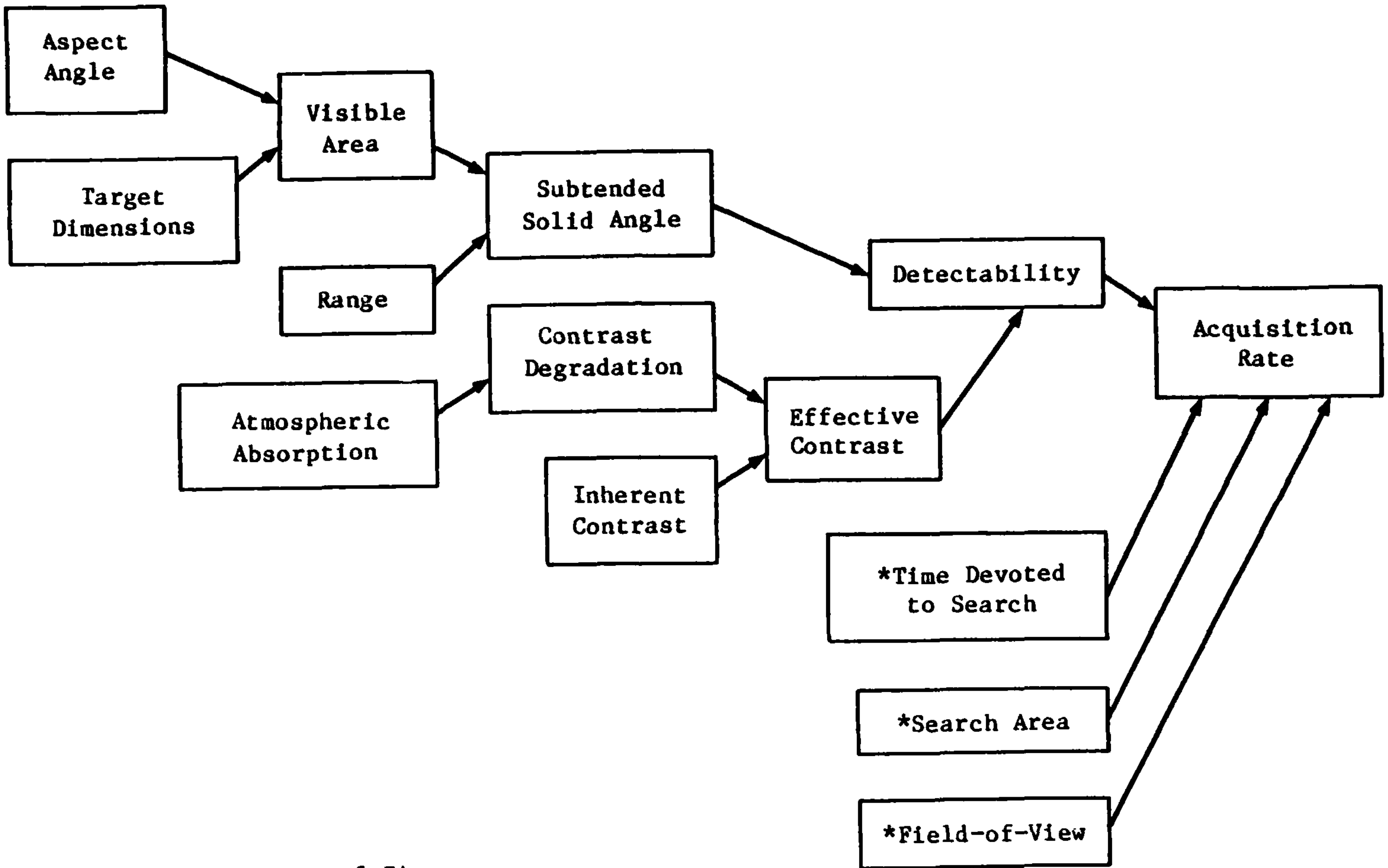
# 6. VISUAL ACQUISITION

The study assumes that if the pilot of the TCAS aircraft visually acquires a conflicting aircraft, he will avoid it. This section will assess the TCAS Traffic Advisory as an improvement to visual acquisition. This probability varies greatly with the characteristics of the target aircraft and with search conditions. It is usually insufficient to assume a single number for this probability for each type of encounter situation. Fortunately, a suitable model was developed during the analysis of test data for the ATARS (IPC) collision avoidance system. This model (see Reference 35) allows the effects of closing rate and target size to be taken into account in computing acquisition probabilities. The basic assumption of the model is that for nominal search conditions (defined below), the acquisition rate (i.e., the probability of visual acquisition per unit time) is proportional to the angular subtense of the target. This assumption has been shown to be valid for visual acquisition data gathered by several different experimenters.

There are theoretical arguments which can be used to extend the model to special cases (for example, to handle cases of poor atmospheric visibility). However, there is no experimental validation of the model under these special conditions, and hence, the analysis which follows is conservative with regard to non-nominal cases.

## 6.1 The Visual Acquisition Model

Figure 6-1 depicts the functional relationship between various factors which influence the visual acquisition rate. It can be seen that the visible area together with the range determines




*Affected by Presence of IA

**FIGURE 6-1**
**FACTORS INFLUENCING ACQUISITION RATE**

the subtended solid angle of the target. For a non-maneuvering collision situation, the visible area is constant. The effective contrast of the target is determined by the range, the atmospheric absorption, and the inherent contrast of the target with the background. The subtended solid angle and the effective contrast together determine the detectability of the target. This detectability is related to the angular proximity which must exist between the target and the foveal center of the pilot's search in order for acquisition to occur. Several factors such as the fraction of time devoted to visual search and the angular area over which the search is conducted also impact the acquisition rate. It is also obvious that a target must be within the pilot's field-of-view in order to be acquired. It should be noted, however, that because a traffic advisory stimulates the pilot to alter his position in the cockpit to search a particular direction, the effective field-of-view of the pilot is greater with traffic advisories than it is without.

The principal mathematical relationship assumed by the model is that under nominal search conditions the acquisition rate (i.e., probability of acquisition per unit of time) is proportional to the solid angle subtended by the target. The acquisition rate can then be written:

$$\lambda = \beta \frac{A}{r^2} \tag{1}$$

where the notation employed is provided in Table 6-1. The probability of no acquisition for search which begins at time $t_1$ before collision and ends at time $t_2$ before collision is given by the integral expression

TABLE 6-1
NOTATION EMPLOYED IN VISUAL ACQUISITION ANALYSIS

| | |
|---|---|
| $A$ | Aircraft visible area |
| $A_x$ | Aircraft visible area when viewed head-on (from 12 o'clock) |
| $A_y$ | Aircraft visible area when viewed broadside (from 3 o'clock) |
| $A_z$ | Aircraft visible area when viewed from directly above |
| $r$ | Range between aircraft |
| $\dot{r}$ | Range rate |
| $t_1$ | Time at which alerted search begins (seconds before closest approach) |
| $t_2$ | Time at which visual acquisition must occur (seconds before closest approach) |
| $V_1$ | Airspeed of TCAS aircraft (own aircraft) |
| $V_2$ | Airspeed of intruder aircraft |
| $\beta$ | Model constant which relates acquisition rate to the subtended solid angle of the target aircraft |
| $\lambda$ | Acquisition rate (instantaneous probability of acquisition per unit of time) |
| $\theta_1$ | Bearing of aircraft 2 as seen from aircraft 1 (degrees clockwise from the 12 o'clock position) |
| $\theta_2$ | Bearing of aircraft 1 as seen from aircraft 2 (degrees clockwise from the 12 o'clock position) |
| $\chi$ | Crossing angle (heading of aircraft 2 less heading of aircraft 1) |

$$P\ [\text{No Acquisition}] = \exp\ [\int_{t_2}^{t_1} \beta\, A/r^2\ dt] \qquad (2)$$

This is a special case of a nonhomogenous Poisson process. If one assumes that the aircraft are on a non-accelerating collision course, then the range decreases at a constant rate and A is constant. Equation (2) then becomes

$$P\ [\text{No Acquisition}] = \exp\ [- \frac{\beta A}{\dot{r}^2}\ \frac{t_1 - t_2}{t_1 t_2}\ ] \quad t_1 \geq t_2 \qquad (3)$$

It can be seen that this expression takes the size of the target, the closing rate, and the time of alerted search into account in explicit fashion. Other factors must be taken into account by proper selection of the model constant $\beta$.

## 6.2 Effects of Search Start Time

It can readily be shown using equation (3) that little improvement in acquisition probability is achieved by beginning visual search earlier than about three times the required acquisition lead time ($t_2$). This is because the added search time occurs while the target is at a greater distance and is less likely to be acquired. An analysis supporting this statement can be found in Reference 35 (page 45). It appears that TCAS alarm thresholds are appropriate from this point of view since the Tau criteria for TCAS traffic advisories (approximately 45 seconds) are roughly three times the required acquisition lead time (15s).

### 6.3 Determination of the Model Constant

For the purpose of this analysis, it will be assumed that $\beta$ is equal to zero (no visual acquisition is possible) under the following conditions:

- Instrument meterological conditions (IMC) exist.
- The target is outside the pilot's field-of-view.
- The pilot is unable to interrupt his other tasks in order to search for the target.
- The pilot has not yet received a TCAS TA.

These assumptions are conservative since (with the exception of the field-of-view requirement) none of these conditions absolutely preclude visual acquisition. In addition, visual search prior to the TCAS TA sometimes results in early acquisition.

The value of $\beta$, which is appropriate for nominal search conditions, has been determined by experiment. In the ATARS (IPC) flight tests, a value of $9 \times 10^4$/sec was derived. In the more limited data base available to TCAS, a value of at least $14 \times 10^4$/sec seems to be indicated. (A higher value is to be expected for TCAS due to the increased bearing accuracy of the TCAS TA.)

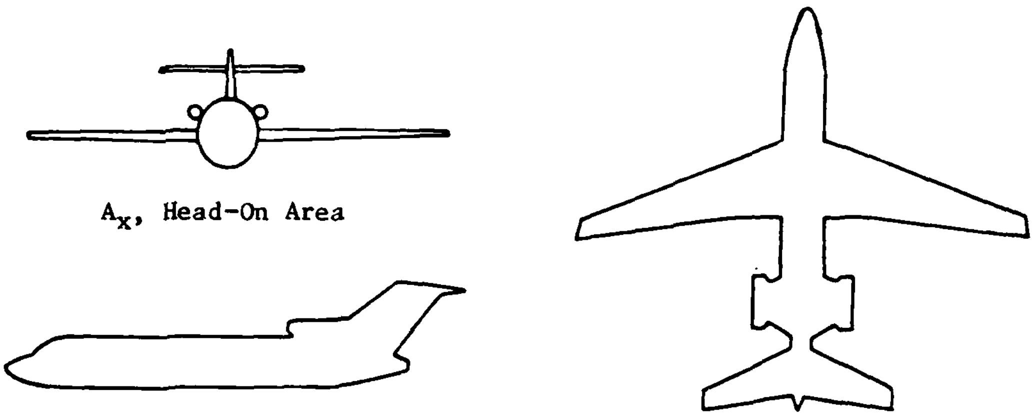
In Reference 35, the value of $\beta$, which applied to unalerted search for VFR flights, was estimated to be approximately 10,000/sec. Thus the presence of the traffic advisory increased the acquisition rate by a factor of approximately 9. This is reasonable since merely alerting the pilot to initiate visual search doubles or triples the amount of time devoted to visual search, and informing him of the direction in which to search decreases angular search area by a factor of 4 or 5. The effect upon alarm rate is multiplicative (i.e., twice the search time in one-fourth the area should increase the acquisition rate by a factor of 8). In the calculations which follow an unalerted search value of 10,000/sec will be assumed.

If more than one pilot is involved in the visual search, then the probability that at least one pilot will acquire is obtained by using a $\beta$ value which is the sum of the $\beta$ values for the individual pilots.

## 6.4 Calculation of Visible Area

The visible area, A, is a function of the target shape, size and the aspect angle with which the target is viewed. A simple technique for calculating an approximate visible area is described in Reference 35. In this approximation, the target aircraft is modeled as if it were an object consisting of only three perpendicular planar surfaces corresponding to the silhouette of the aircraft when viewed head-on, broadside, and from directly above (see Figure 6-2). Appropriate values for the areas of these three surfaces are provided in Table 6-2 for three representative types of aircraft. For the calculations which follow, it will be assumed that the target aircraft is viewed from the horizontal plane, and hence, that only $A_x$ and $A_y$ contribute to the visible area. The visible area is then approximated as follows:

$$\begin{aligned} a_x &= A_x \, [\sin\theta_2] \\ a_y &= A_y \, [\cos\theta_2] \\ A &= \max(a_x, a_y) + \frac{1}{3}\min(a_x, a_y) \end{aligned} \tag{4}$$



$A_x$, Head-On Area

$A_y$, Broadside Area

$A_z$, Above Area

**FIGURE 6-2**
**AIRCRAFT VISIBLE AREAS WHEN VIEWED FROM THE THREE PRINCIPAL COORDINATE AXES**

TABLE 6-2
PRINCIPAL AREAS FOR THREE AIRCRAFT TYPES

| TYPE AIRCRAFT | WINGSPAN | HEAD-ON AREA, $A_x$ | BROADSIDE AREA, $A_z$ | ABOVE AREA, $A_z$ |
|---|---|---|---|---|
| Single-Engine General Aviation | 32 ft | 20 $ft^2$ | 100 $ft^2$ | 200 $ft^2$ |
| Multi-Engine Jet Transport (Boeing 727) | 108 ft | 330 $ft^2$ | 1650 $ft^2$ | 3100 $ft^2$ |
| Military Jet Interceptor | 45 ft | 40 $ft^2$ | 200 $ft^2$ | 440 $ft^2$ |

## 6.5 Required Visual Acquisition Time

According to the model, when the target is approaching on a collision course from within the field-of-view under nominal search conditions, the pilot is certain to acquire at some point since the angular size of the target will eventually become very large. But visual search must be regarded as unsuccessful unless acquisition occurs with enough lead time to allow the pilot to evaluate and react to the sighting. In calculations which follow, a late acquisition is defined as any acquisition which occurs at less than 15 seconds to projected collision. In any set of actual encounters, there would be some cases in which later acquisitions were successful in allowing visual avoidance and some in which earlier acquisitions were unsuccessful. The 15 second value is intended to represent an average requirement, not a worst case value.

## 6.6 Calculation of Visual Acquisition Probabilities

We will now calculate visual acquisition probabilities for some particular cases of interest. For these calculations, it is assumed that the aircraft are approaching on unaccelerated flight paths with constant airspeeds. Let the crossing angle, $\chi$, be defined as the difference in headings of the two aircraft (see Figure 6-3). Thus, $\chi = 0^{\circ}$ corresponds to parallel flight and $\chi = 180^{\circ}$ corresponds to a head-on encounter. $\chi$ can be written in terms of the bearings as follows:

$$\chi = \pi + \theta_1 - \theta_2 \tag{5}$$

A necessary condition for a collision course is

$$V_1 \sin \theta_1 + V_2 \sin \theta_2 = 0 \tag{6}$$

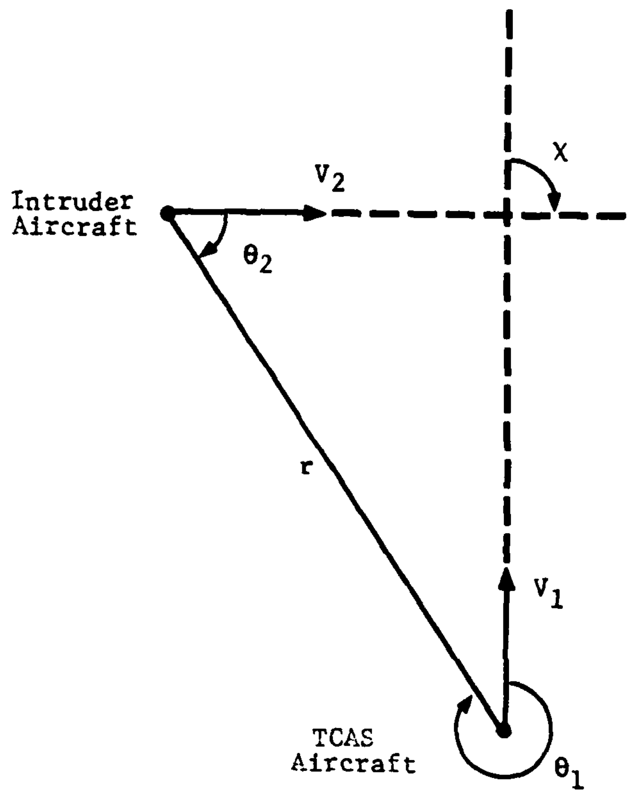



**FIGURE 6-3**
**NOTATION EMPLOYED IN DESCRIPTION OF ENCOUNTER GEOMETRY**

Taken together, these two equations define a unique pair of bearings which must exist for a collision to occur at a particular crossing angle. The range rate which then exists is

$$\dot{r} = -V_1 \cos \theta_1 - V_2 \cos \theta_2 \qquad (7)$$

The probability of visual acquisition before 15 seconds is given by equation (3) with $t_2$ = 15 seconds. Table 6-3 provides an example of the values of the relevant quantities for crossing angles from 0 to 180 degrees when the TCAS aircraft has an airspeed of 250 knots and the intruder is a small aircraft with an airspeed of 130 knots.

Several points are worth noting in Table 6-3. First, the acquisition probability is greater at shallow angles when the closing rate is smaller. It decreases to a minimum in the head-on geometry. Because the TCAS aircraft is the faster aircraft, all collision geometries require the intruder to approach from a bearing sector of approximately $\pm$ 30 degrees centered upon the 12 o'clock bearing. For collision geometries, the slower aircraft always approaches the faster from somewhere in the forward hemisphere. This result means that the intruder is likely to be within the field-of-view when the TCAS aircraft is the faster of the pair.

In averaging acquisition probabilities, some care must be taken to weight the values according to the likelihood with which each geometry occurs. If the heading of each aircraft is uniformly distributed between $0^o$ and $360^o$, then all crossing angles are equally likely. For two aircraft selected

TABLE 6-3
CALCULATION OF VISUAL ACQUISITION PROBABILITIES - AN EXAMPLE

| | |
|---|---|
| Own Airspeed: | 250 knots |
| Intruder Airspeed: | 130 knots |
| Intruder Size: | $A_x$ = 20 sq. ft. $A_y$ = 100 sq. ft. |
| Time Search Begins: | $t_1$ = 40 sec |
| Time at Which Visual Required: | $t_2$ = 15 sec |
| Model Constant: | $\beta$ = 140000/sec |

| $\chi$ | $\theta_2$ | $\theta_1$ | $\dot{r}$ | A | P(visual) |
|---|---|---|---|---|---|
| 0.0 | 180.0 | 0.0 | -120.0 | 20.0 | 0.942 |
| 10.0 | 159.5 | -10.5 | -124.0 | 41.2 | 0.996 |
| 20.0 | 140.8 | -19.2 | -135.4 | 68.3 | 1.000 |
| 30.0 | 124.7 | -25.3 | -152.0 | 86.0 | 1.000 |
| 40.0 | 110.9 | -29.1 | -172.1 | 95.8 | 0.999 |
| 50.0 | 99.1 | -30.9 | -194.0 | 99.8 | 0.996 |
| 60.0 | 88.7 | -31.3 | -216.6 | 100.1 | 0.987 |
| 70.0 | 79.3 | -30.7 | -239.1 | 99.5 | 0.972 |
| 80.0 | 70.6 | -29.4 | -261.0 | 96.5 | 0.945 |
| 90.0 | 62.5 | -27.5 | -281.8 | 91.8 | 0.906 |
| 100.0 | 54.8 | -25.2 | -301.1 | 85.6 | 0.855 |
| 110.0 | 47.5 | -22.5 | -318.8 | 78.2 | 0.793 |
| 120.0 | 40.3 | -19.7 | -334.5 | 69.8 | 0.721 |
| 130.0 | 33.4 | -16.6 | -348.1 | 60.6 | 0.641 |
| 140.0 | 26.6 | -13.4 | -359.4 | 50.7 | 0.552 |
| 150.0 | 19.8 | -10.2 | -368.4 | 40.2 | 0.455 |
| 160.0 | 13.2 | -6.8 | -374.8 | 29.3 | 0.348 |
| 170.0 | 6.6 | -3.4 | -378.7 | 23.7 | 0.287 |
| 180.0 | 0.0 | 0.0 | -380.0 | 20.0 | 0.247 |

Average (unweighted) = 0.771

at random, an unweighted average of the values in Table 6-3 would provide the average probability of visual acquisition. However, if aircraft are allowed to encounter each other in an unstructured fashion, there will be more encounters with aircraft which are flying at higher speeds relative to the TCAS aircraft. In this case the average should be weighted according to relative speed.

Table 6-4 provides the average probabilities of visual acquisition for a combination of airspeeds and intruder types. In computing these averages, all crossing angles were assumed to be equally likely. It was also assumed that visual acquisition was impossible if the intruder was approaching from behind at any bearing from 5 to 7 o'clock. The value of $\beta$ for unalerted search is taken from Reference 35.

The extent to which a change in the value of the parameter $\beta$ can affect acquisition probabilities can be further characterized by using equation (3) to derive the following relationship:

$$q_1 = q_0^{\beta_1/\beta_0} \tag{8}$$

where $q_1$ and $q_0$ are the probabilities of acquisition failure for parameter values $\beta_1$ and $\beta_0$, respectively. Note that this relationship is independent of the target area, closing rate, or time of search. A plot of $q_1$ versus $q_0$ is provided in Figure 6-4 for various ratios of the model parameter. Earlier it was suggested that the presence of an automated traffic advisory can increase the value of $\beta$ by an

TABLE 6-4
AVERAGE PROBABILITIES OF VISUAL ACQUISITION

| | |
|---|---|
| Own Airspeed: | $V_1$ = 250 knots |
| Search Start Time: | $t_1$ = 40 sec |
| Required Acquisition Time: | $t_2$ = 15s before CPA, or 25s (at time of RA) |
| Model Constant: | $\beta$ = 140000. (single pilot, alerted) |
| | $\beta$ = 280000. (two pilots, alerted) |
| | $\beta$ = 20000. (two pilots, unalerted) |

| OWN AIRSPEED (kt) | INTRUDER TYPE* | INTRUDER AIRSPEED (kt) | INTRUDER SIZE (SQ. FT.) | | P(VISUAL ACQUISITION | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | SINGLE PILOT ALERTED | TWO PILOTS ALERTED | | TWO PILOTS UNALERTED |
| | | | $A_x$ | $A_y$ | 15 Sec | 15 Sec | 25 Sec | 15 Sec |
| 130 | GA | 130 | 20 | 100 | 0.870 | 0.949 | | 0.538 |
| 180 | GA | 130 | 20 | 100 | 0.831 | 0.921 | | 0.479 |
| 250 | GA | 130 | 20 | 100 | 0.771 | 0.880 | 0.705 | 0.312 |
| 250 | GA | 180 | 20 | 100 | 0.723 | 0.837 | 0.663 | 0.353 |
| 250 | JT | 250 | 330 | 1650 | 0.992 | 1.000 | 0.980 | 0.802 |
| 500 | JT | 500 | 330 | 1650 | 0.885 | 0.957 | 0.782 | 0.557 |
| 250 | MIL | 250 | 40 | 200 | 0.775 | 0.881 | 0.718 | 0.436 |
| 500 | MIL | 500 | 40 | 200 | 0.528 | 0.652 | 0.339 | 0.257 |

* GA = General Aviation, single engine
JT = Jet Transport
MIL = Military, jet fighter

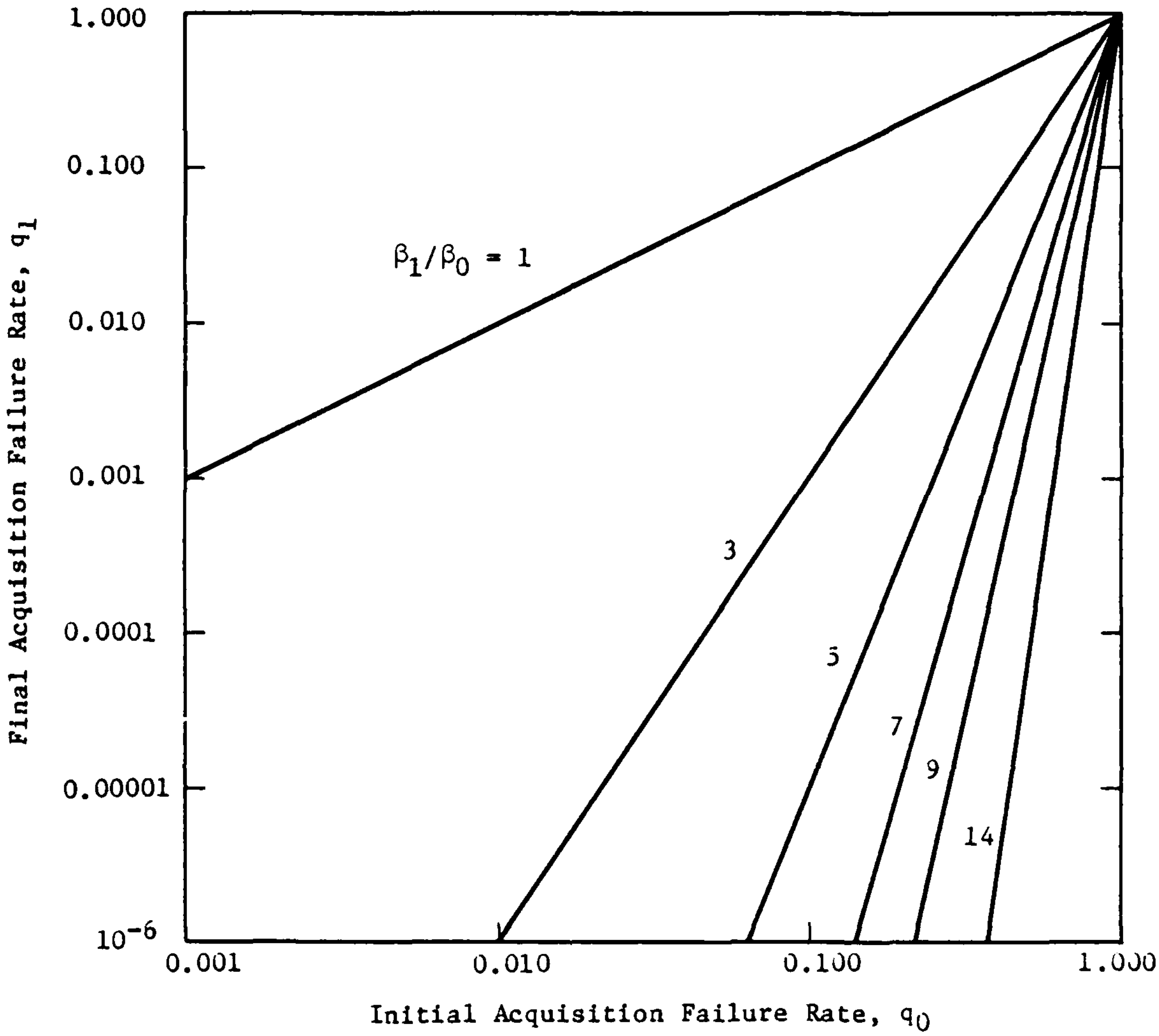



**FIGURE 6-4**
**EFFECT UPON THE VISUAL ACQUISITION FAILURE RATE**
**OF AN INCREASE IN THE PARAMETER β**

order of magnitude or more. Under this condition, it can be seen that for $q_0$ significantly less than unity, the presence of the traffic advisory will decrease the acquisition failure rate by several orders of magnitude. When $q_0$ is near unity (very little chance of successful acquisition), the presence of the traffic advisory cannot reduce the failure rate to negligible levels. However, it can be shown from equation (8) that for $q_0$ near unity, the probability of successful visual acquisition is increased by a factor of approximately $\beta_1/\beta_0$.

## 6.7 General Conclusions

The following general conclusions concerning visual acquisition are supported by the analysis presented in this chapter:

1. Under nominal search conditions, a TCAS II traffic advisory can increase the instantaneous rate of visual acquisition by an order of magnitude or more.

2. Visual acquisition probabilities are low for head-on encounters with smaller aircraft. In general, the increased size of jet transport intruders more than compensates for their increased speed making them easier to acquire.

## 6.8 Specific Conclusions

The following results apply to TCAS when good Visual Meteorological Conditions exist. No visual acquisition was assumed for intruders approaching from behind, from 5 to 7 o'clock. These conclusions result from averaging the contributions of encounters with the three types of aircraft listed in Table 6-4. The highest intruder airspeed was used for each aircraft type in the table, providing a more conservative result. The values for two pilots, alerted, were used, representing own aircraft (an air carrier with at least two crew members, alerted by TCAS).

1. The weighted average for NMAC data gives an overall probability of not acquiring a threat by 15 seconds before CPA to be 0.17 (acquisition probability = .83).

2. The weighted average for NMAC data gives an overall probability of not acquiring a threat by 25 seconds before CPA (the time of the RA) to be 0.35 (acquisition probability = .65).

Appendix L applies the visual acquisition model to the usual case that a pilot experiences when traffic advisories are provided by the ATC controller over VHF radio. There it is shown that the model predicts a typical probability of visual acquisition for those conditions to be around 30 percent, much lower than the model predictions which are appropriate for use in NMAC geometries. These results are generally agreed to be consistent with pilot experience, and provide some level of confidence in the validity of the model.

# 7. FAULT TREE FOR TCAS SAFETY ANALYSIS

The fault tree constructed for this study provides both a qualitative and a quantitative means to identify and analyze failure modes in the overall system. A fault tree identifies all possible means by which a single undesired event (in this case, a critical near midair collision) can occur, organizes them into a logical structure to study the processes leading to failures, and systematically identifies all their root causes and interactions. If a failure can be caused by the occurrence of one of several events, the events are represented in a tree structure as combining at a logical OR "gate." If all the events must fail to cause a system failure, they are combined in the tree structure with a logical AND gate (Reference 2). Since all contributory causes of failure are identified, the quantitative analysis accurately represents the impact of a particular failure mode on the overall failure probability.

The fault tree in this study combines a comprehensive analysis of TCAS failure mechanisms with non-TCAS events. The interactions between them are fundamental to the effect of TCAS on the NMAC hazard. Thus, the fault tree is not merely a TCAS fault tree, nor is it a comprehensive NMAC fault tree. Instead, it is a form of NMAC fault tree with considerable detail for TCAS-related branches.

In this section, the development of the fault tree will be presented and the significance of the complete tree discussed. The methodology for the quantitative analysis of the tree will be described, followed by the reduction and analysis of the tree.

## 7.1 Development of Fault Tree

The approach taken in the development of the fault tree makes use of the fact that TCAS issues advisories only in the last 35 to 45 seconds prior to closest point of approach (CPA). We assume that any events that can lead to an NMAC that occur prior to approximately one minute before CPA have already occurred.

There are two primary types of TCAS failures which we are interested in evaluating:

1. Two aircraft are on flight paths such that the pilot will need to make a maneuver in order to avoid an NMAC; TCAS does not provide an advisory adequate to enable the pilot to avoid it. We will refer to this as an "Unresolved NMAC".

2. Two aircraft are on flight paths such that *if* no maneuver is made, an NMAC will not occur (the aircraft will pass safely in the vertical dimension). A faulty instruction is issued (in particular, a Resolution Advisory) which is followed, causing a critical NMAC to occur. We will refer to this as an "Induced NMAC".

The fault tree is set up so as to measure these two factors separately. This is possible because, in general, the failure mechanisms for these events are different. Failures of the first type will result from TCAS not displaying an advisory or the pilot not using it. Once an advisory is displayed, it will usually lead to safe separation (since a displacement of 100 feet or less in the correct direction removes the aircraft from an NMAC). In the second case, an advisory is required in order for failure to occur.

The distinction between these two types of failures enables us to establish a first set of immediate and sufficient causes of NMACs: either an NMAC was about to occur, but was not avoided; or one was not about to occur, but was induced. These circumstances define the second level events illustrated in Figure 7-1. These two events become "top events" of two subtrees.

In the tree in this study, the structure does not indicate any time order to the occurrence of events; in addition, certain failure probabilities will actually be conditional probabilities, with the condition not listed as an event within the tree. An ideal fault tree describes not only what happens, but the order in which the events occur and all preconditions to an event. However, these conditions will be explained and taken into account in the quantitative analysis.

To assist in the following explanation of the fault tree, a convention has been designed to aid in identifying and locating events within the tree. Events are given a unique 3-digit numeric identifier. Also, a level number indicates how far down in the tree the event will be found. Each event, except the top event, can be referenced by its level and event number. Thus the two events at level 2 in Figure 7-1 are events 2-000 and event 2-500. In addition, event numbers are assigned to the tree in the following manner:

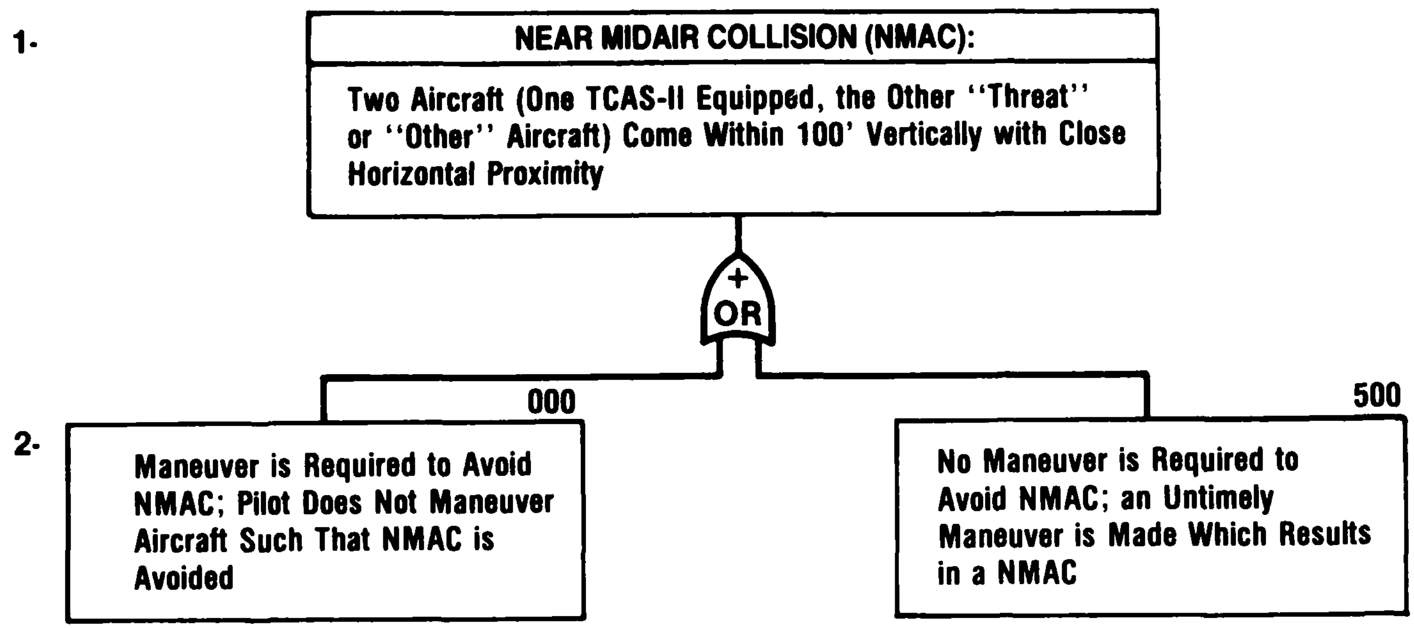



FIGURE 7-1
TCAS FAULT TREE: TOP EVENT (CRITICAL NMAC)

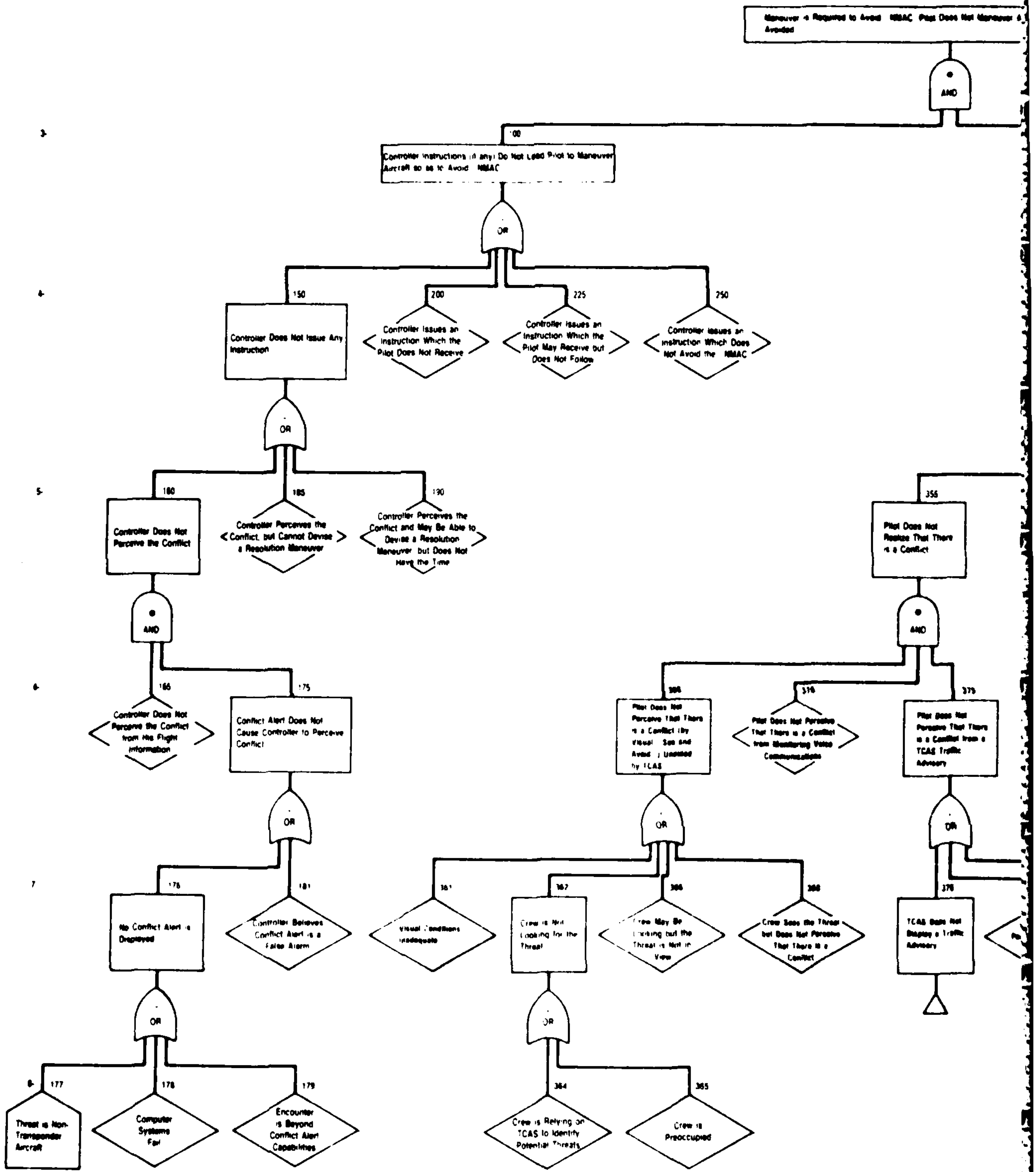
Event numbers 000 to 499 are on the "000 branch" and will be found below event 000 (unresolved NMAC). Event numbers 500 to 999 are on the "500 branch" (induced NMAC). On each branch, events are given increasing numbers from top to bottom and from left to right. "Round" numbers like 100, 600, and 150 will be found closer to the top; intermediate numbers, like 179, 378, and 732 will be found at or near the bottom.

### 7.1.1 The 000 Branch of the Tree, Unresolved NMAC

The 000 Branch of the fault tree, Unresolved NMAC, is shown in Figure 7-2. The failure to resolve the NMAC is in the failure of two principal events: the controller failing to resolve with instructions (event 3-100) and the pilot failing to maneuver on his own (event 3-300). In turn, pilot failure is the failure of the pilot to see-and-avoid, aided by the TCAS TA display (event 4-350), and the failure of a TCAS RA to avoid the NMAC (event 4-410). Each branch will be discussed in turn.

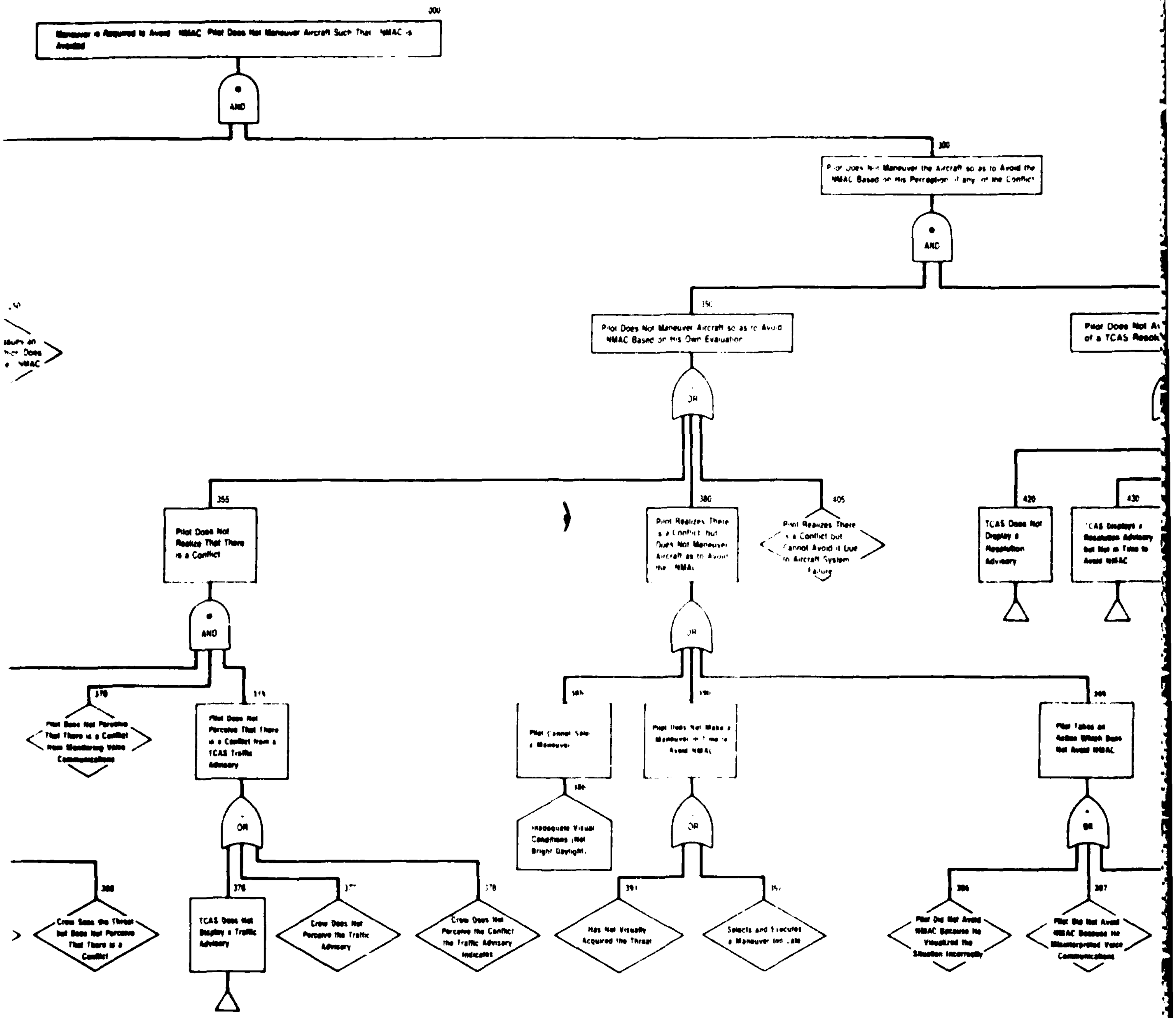
Controller Branch: Event 3-100. The System Safety study did not analyze the possibility of pilot/controller interaction during the time interval of the TCAS alert. Nonetheless, branch 100 of the fault tree is provided for these actions, as well as for those the controller might take independently of the pilot. Should pilot/controller interactions be identified, they can be evaluated based on this branch of the tree.

This branch describes failures within the following process of resolving a conflict: the controller perceives the conflict, either by monitoring his display or by the presence of a Conflict Alert; he determines a maneuver that will resolve the



Maneuver is Required to Avoid NMAC Pilot Does Not Maneuver
Avoided
AND
3.
100
Controller Instructions (if any) Do Not Lead Pilot to Maneuver Aircraft so as to Avoid NMAC
OR
4.
150
Controller Does Not Issue Any Instruction
200
Controller Issues an Instruction Which the Pilot Does Not Receive
225
Controller Issues an Instruction Which the Pilot May Receive but Does Not Follow
250
Controller Issues an Instruction Which Does Not Avoid the NMAC
OR
5.
160
Controller Does Not Perceive the Conflict
185
Controller Perceives the Conflict, but Cannot Devise a Resolution Maneuver
190
Controller Perceives the Conflict and May Be Able to Devise a Resolution Maneuver but Does Not Have the Time
355
Pilot Does Not Realize That There is a Conflict
AND
AND
6.
165
Controller Does Not Perceive the Conflict from His Flight Information
175
Conflict Alert Does Not Cause Controller to Perceive Conflict
360
Pilot Does Not Perceive That There is a Conflict (by Visual See and Avoid) Unaided by TCAS
370
Pilot Does Not Perceive That There is a Conflict from Monitoring Voice Communications
375
Pilot Does Not Perceive That There is a Conflict from a TCAS Traffic Advisory
OR
OR
OR
7
176
No Conflict Alert is Displayed
181
Controller Believes Conflict Alert is a False Alarm
361
Visual Conditions Inadequate
362
Crew is Not Looking for the Threat
366
Crew May Be Looking but the Threat is Not in View
368
Crew Sees the Threat but Does Not Perceive That There is a Conflict
376
TCAS Does Not Display a Traffic Advisory
OR
OR
8.
177
Threat is Non-Transponder Aircraft
178
Computer Systems Fail
179
Encounter is Beyond Conflict Alert Capabilities
364
Crew is Relying on TCAS to Identify Potential Threats
365
Crew is Preoccupied


7-7

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**TCAS FA**
**(UNRESC**

2

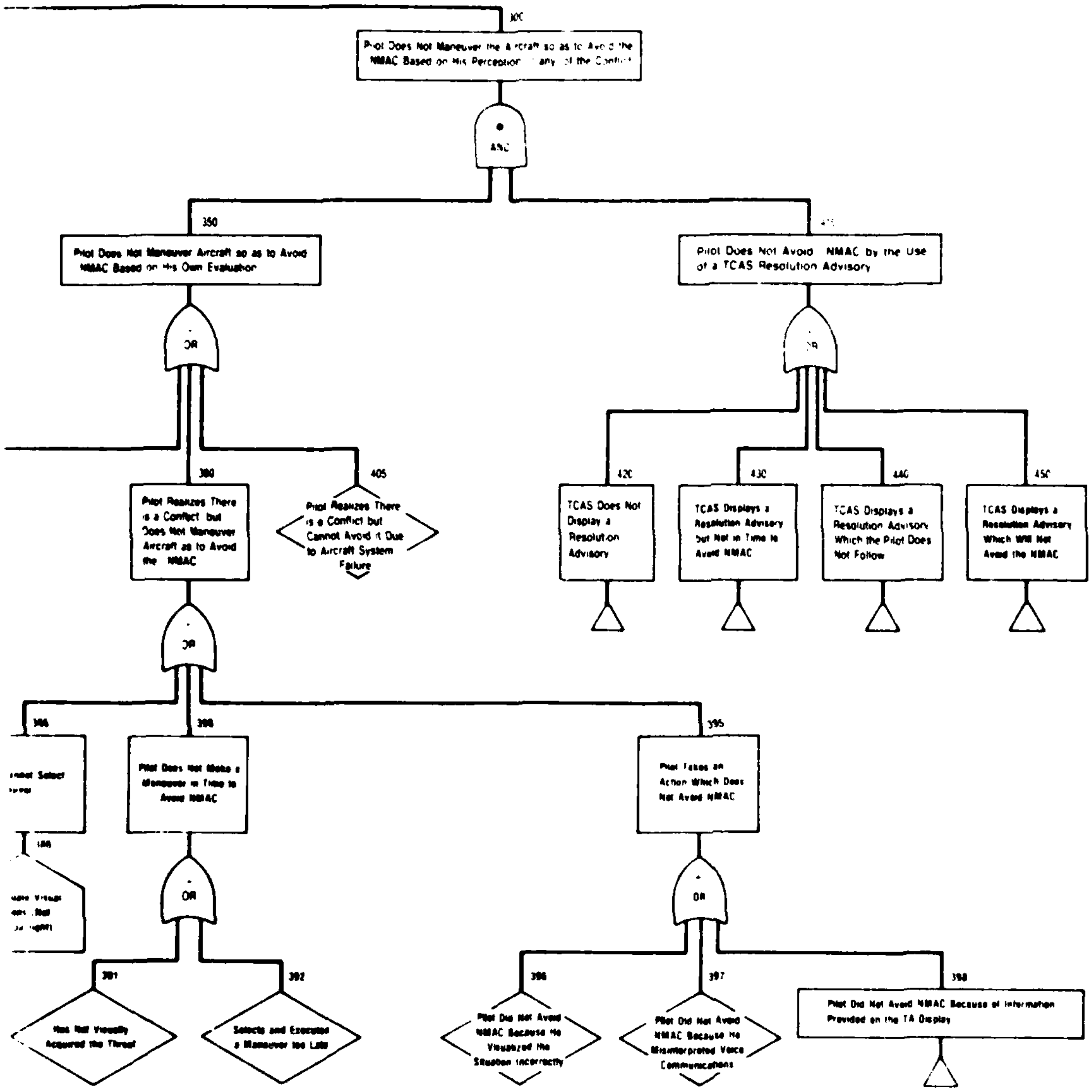


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FIGURE 7-2
TCAS FAULT TREE, BRANCH 000
(UNRESOLVED CRITICAL NMAC)



3

conflict and communicates it to the pilot; the pilot makes a maneuver which resolves the conflict. The fault tree structure arises from this process by enumerating the methods by which each of these steps could fail.

As there is an automated system (Conflict Alert) designed to bring conflicts to the controller's attention and provide a measure of redundancy to the system (thus the "AND" gate under event 5-160), the possibility of its failure is included as well.

Pilot "See-and-Avoid" Branch: Event 4-350. This branch has the most commonality when comparing TCAS and non-TCAS safety. This is primarily due to the function of TCAS TAs, which is to provide an aid to the pilot's see-and-avoid process. They increase the probability that the pilot will see a threat; but the probability of avoiding the NMAC once the threat is seen is the same.

The process of the pilot avoiding a conflict is simpler in form than the controller process described above. Failure to avoid the NMAC can occur if the pilot fails to realize there is conflict (event 5-355), if he fails to select and execute a maneuver (event 5-380), or if the aircraft is unable to execute the maneuver (event 5-405).

Failure to determine the existence of a conflict requires the failure of all three mechanisms by which the pilot can determine that a conflict exists. These mechanisms and their failure events are visual acquisition, unaided by TCAS (event

6-360); voice communications (event 6-370); and the TCAS TA display (visual acquisition is not assumed) (event 6-375). As the failure of all three is required, they are connected by an "AND" gate to event 5-355.

If the pilot does perceive the conflict, he will then select and execute a maneuver which will avoid the NMAC. If the conflict was perceived by means of voice communications or a TA, then visual acquisition must occur; this can fail by either the aircraft being in adverse visual conditions (IMC or other difficult conditions such as glaring sun or haze) (event 7-386) or by the pilot not being able to acquire the threat in time to maneuver (event 7-391). If the threat is visually acquired, an escape maneuver should be made. The possibility of a failure to maneuver appropriately is treated as a human factors variable. The possibility of the TA misleading the pilot or the pilot taking an inappropriate action to avoid the NMAC, by using the TA instead of visual acquisition as the basis for a maneuver, is described by event 7-398.

Resolution Advisories: Branch 4-410. TCAS Resolution Advisory faults have been analyzed in great detail. Four general classes of these faults are listed here; a complete listing of the branches is presented in Appendix G. The four classes of faults are:

- No Resolution Advisory is displayed (event 5-420)

- A Resolution Advisory is displayed but not in time (event 5-430)

- The Pilot does not follow the RA (event 5-440)

- The Resolution Advisory is Inadequate to Avoid NMAC (the wrong sense or strength is given, or it is not displayed long enough) (event 5-450)

### 7.1.2 The 500 Branch of the Fault Tree, Induced NMAC

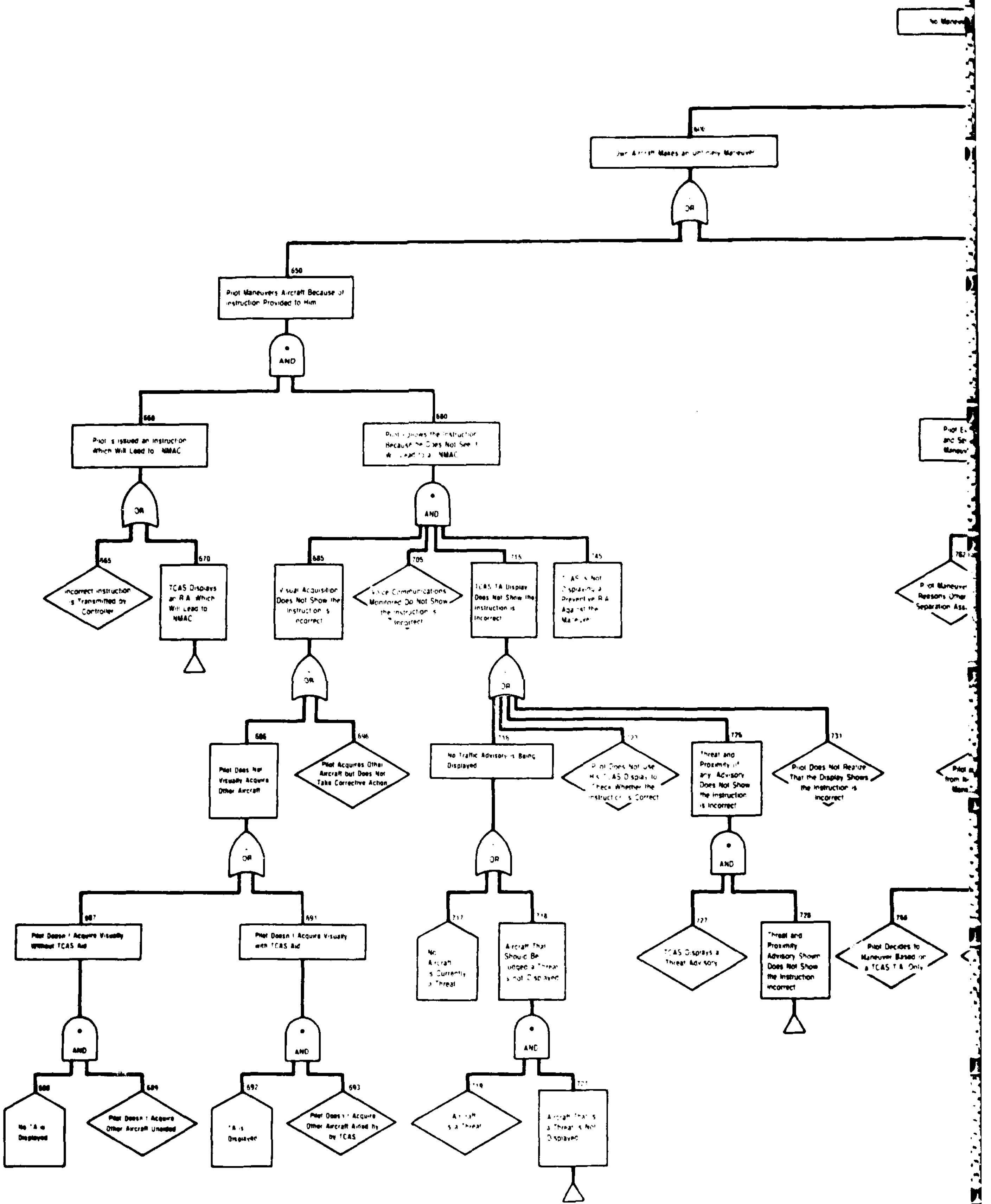
The logical interconnection of events may be more difficult to see in the Induced NMAC branch of the tree. This branch must deal with the source of the decision to maneuver -- either the pilot, TCAS, or the controller -- and any mechanisms which can override this decision, not all of which apply in every scenario.

Branch 500 is shown in Figure 7-3. In order for an induced critical NMAC to occur (event 2-500), two things must happen:

- The pilot must maneuver the aircraft (event 3-600) in such a fashion as to create an impending NMAC within the short time period prior to CPA for which the fault tree applies (approximately 1 minute)

- Neither the controller nor TCAS issues a last-minute instruction to avert the NMAC (events 4-810 and 4-900)

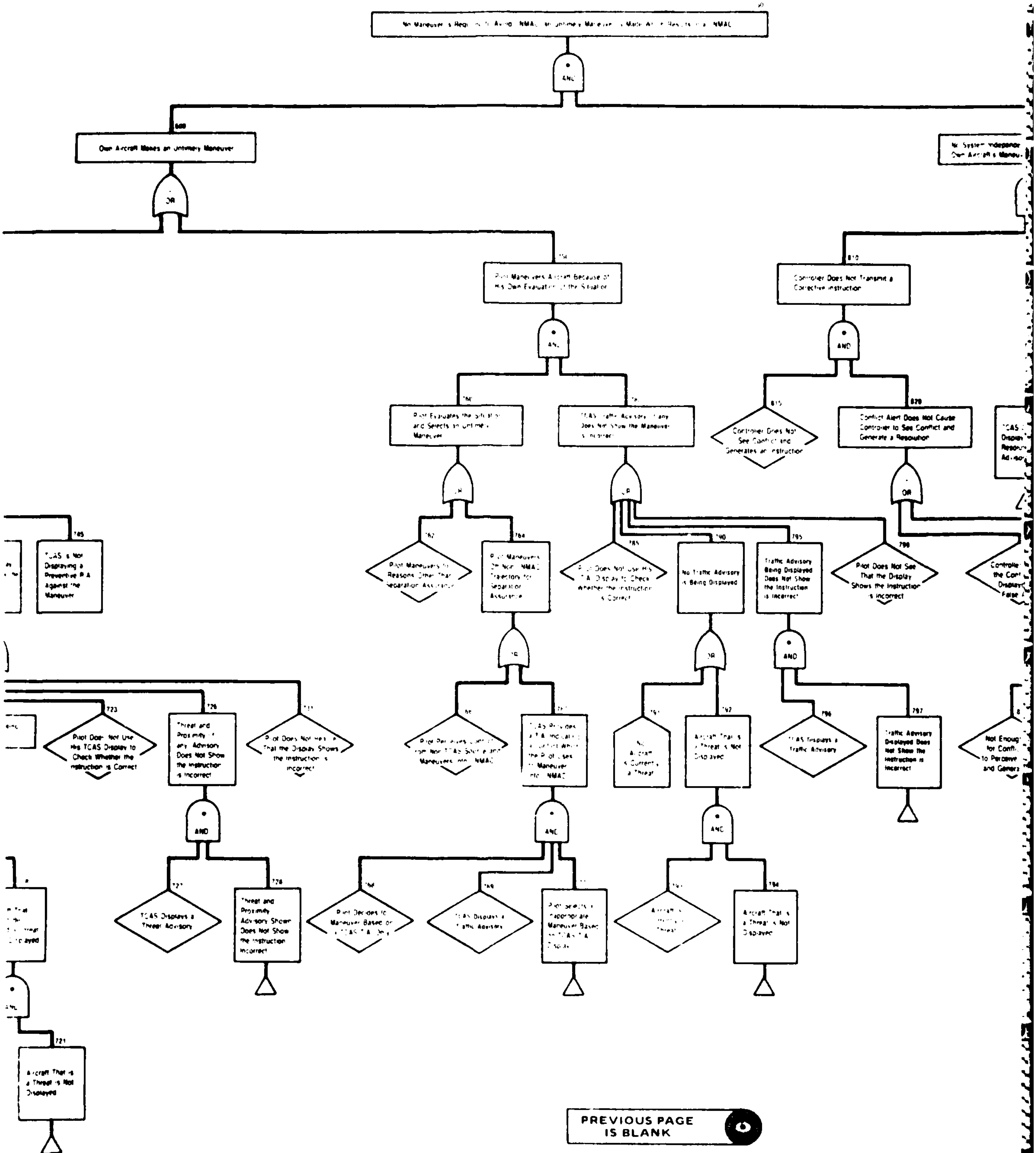
Source of the Decision to Maneuver. Of primary interest on this branch of the fault tree is the reason the maneuver is made. The fault tree divides this into two types: an inappropriate instruction issued to the pilot (event 4-650) or the pilot's choice of an inappropriate maneuver because of his evaluation, using all information available to him (including the TCAS TA display) (event 4-750).



Pilot Maneuvers Aircraft Because of Instruction Provided to Him
AND
OR
Pilot Doesn't Acquire Visually Without TCAS Aid
Pilot Doesn't Acquire Visually with TCAS Aid
TCAS Displays a Threat Advisory
Pilot Decides to Maneuver Based on a TCAS TA Only


7-13

1



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2

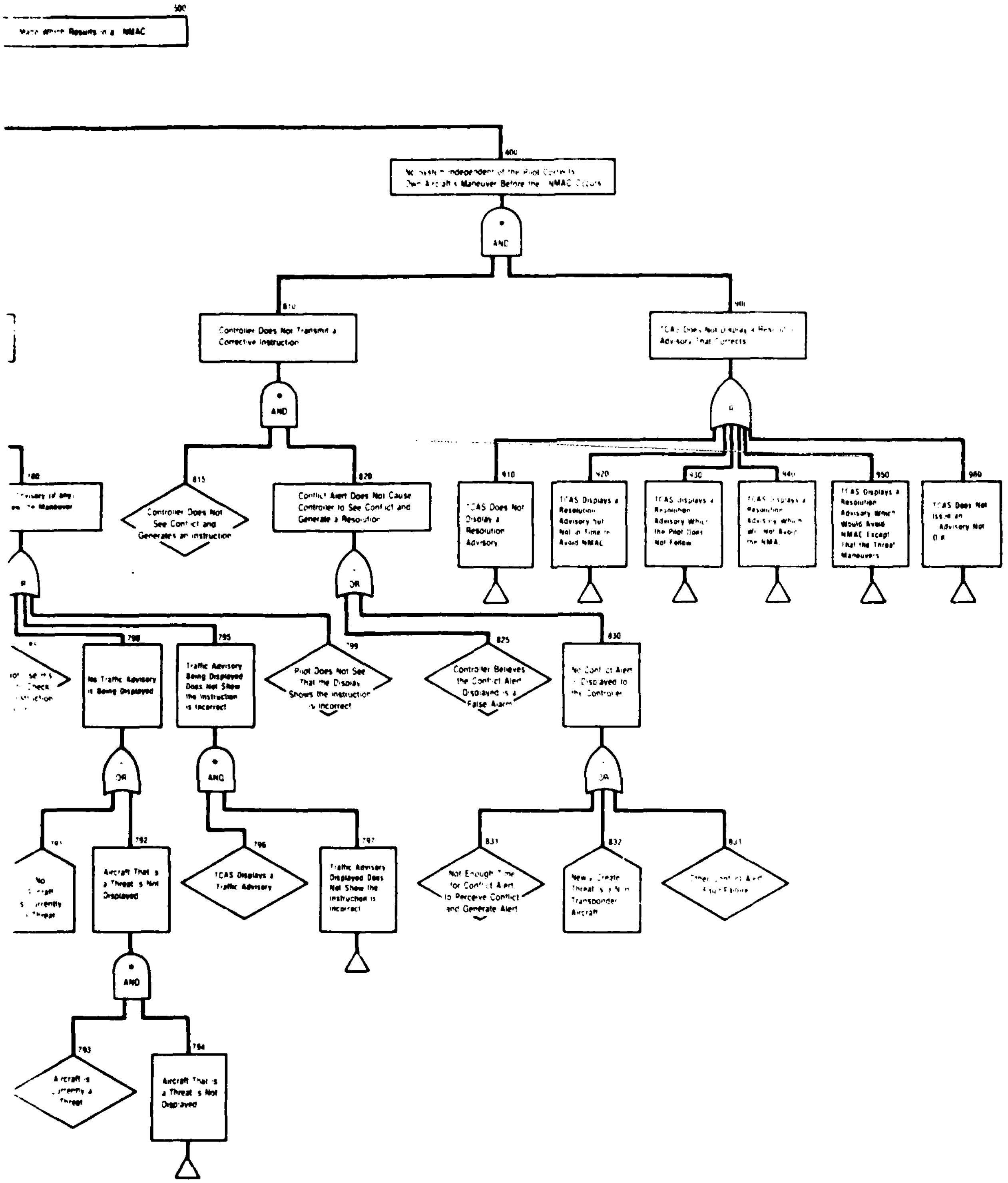


**FIGURE 7-3**
**TCAS FAULT TREE, BRANCH 500**
**(INDUCED CRITICAL NMAC)**

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3

Under event 4-650, there are two sources of instructions which can lead to NMAC: the controller (event 6-665) and TCAS RAs (event 6-670). We are not concerned with the causes of the controller's inappropriate instruction, but rather TCAS' ability to resolve them, and thus event 6-665 is not developed further. We are concerned with causes of inappropriate TCAS RAs; a full development of these faults is contained in Appendix G.

Given that an inappropriate instruction was issued, we assume it is followed (leading to an NMAC) unless the pilot determines it is incorrect and takes an alternate action. The four basic sources of information that can indicate to the pilot the need for alternate action, and the events that describe their failure, are:

- Visual acquisition (event 6-685). We assume that if the pilot can visually acquire the other aircraft, he can avoid the NMAC. The TCAS TA can assist the pilot's visual acquisition. Failures are described under event 6-685.

- Voice communications (event 6-705). There is a possibility that the pilot could determine that alternate action is required by what he hears over the radio.

- TCAS Traffic Advisory (event 6-715). There is also a possibility that the TA itself can show an instruction to be incorrect. (This does not imply the pilot maneuvers on the TA; it is a case of not following an instruction because the TA makes it appear incorrect).

- TCAS Resolution Advisory (event 6-745). In the case of an instruction being issued by the controller, if a preventive RA is being displayed, it could act to avoid the induced NMAC.

The TCAS TA rarely provides any reason not to take an incorrect RA; thus, visual acquisition (aided by the TA, which will almost always be present) is the primary means by which any incorrect RA is recognized as such. The TCAS TA and RA both provide mechanisms to avoid an NMAC due to an incorrect controller's instruction.

In those cases where the pilot selected an inappropriate maneuver (event 4-750), we assume the pilot used the TA display to help locate and avoid any proximate aircraft. Reasons why failure might occur are detailed under event 5-780.

The maneuvers selected are divided into those which are made for separation assurance (event 6-764) and those which are made for other reasons (event 6-762). Those made for separation assurance are further divided into those where the pilot determined the need to maneuver based on information TCAS displayed (event 7-766) or other reasons (event 7-767). No further development is done for events 6-762 and 7-767; we will only be interested in TCAS' ability to resolve these maneuvers and not in the pilot's reasons for selecting them.

For the case where the pilot might misuse the TA display to make a maneuver leading to an NMAC, three conditions must be satisfied:

- A Traffic advisory must be displayed (event 8-769)

- The pilot must choose to maneuver based on the TA (event 8-768)

- The maneuver selected must be such as to lead to a critical NMAC (event 8-771)

Issuance of an Instruction to Avert the NMAC. The structure under event 3-800 describes the failures of mechanisms which can act to avert the induced NMAC. The possibility exists that the controller (event 4-810) can recognize the conflict and correct it, but this possibility is not analyzed in the study. Similarly, the possibility that TCAS corrects the maneuver with an RA (event 4-900) is noted but not assessed. In the case of an RA inducing an NMAC because the intruder made a sudden maneuver (event 6-670), it is possible to receive an "advisory not OK" (event 5-960) which can alert the pilot to stop executing the RA. This analysis does not account for that feature either.

## 7.2 A Methodology for Quantifying the Fault Tree

The TCAS fault tree provides a means by which the interactions of various elements of the system can be assessed from a System Safety point of view. The characterization of the airspace and the failure rates generated in earlier sections provide the probabilities of occurrence of events within the fault tree. The structure of the fault tree determines how these probabilities combine to form the estimate of the probability of the top event. Sensitivity analysis (to be discussed in Section 8) will be performed to assess the impact of changes in failure rates and assumptions on the performance of the system as a whole.

We have modified the normal process for quantifying a tree in order to assess the Risk Ratio -- that is, the risk relative to the current risk. While the relative risk is usually the desired information, the absolute risk of encountering a critical NMAC can be obtained by multiplying the Ratio by the current risk, $1 \times 10^{-5}$ per hour, as found in Section 3.3.4.

### 7.2.1 Approach to Quantifying the Fault Tree to Obtain the Risk Ratio

In classical fault tree analysis, one obtains probabilities for all the primary (bottom) events in the tree. These probabilities are combined at the gates in the tree, going from the lowest level to the top gate, in order to estimate the probability of the top event. If events are independent, probabilities sum at OR gates and multiply at AND gates. If interdependent, probabilities can range from the sum to the maximum of the probabilities at an OR gate and from the product to the minimum at an AND gate. The level of interdependence determines where within these limits the probability will be.

The fault tree structure is used as a qualitative mechanism to identify all possible TCAS failure mechanisms, as well as to evaluate interdependencies among TCAS and the ATC environment. As a quantitative mechanism, we will use the fault tree to calculate the relative risk (the overall Risk Ratio). For purposes of the fault tree analysis, this involves replacing failure rates for non-TCAS-related branches with 1.0 at AND gates and 0.0 at OR gates (where these gates combine with a

TCAS branch) and computing the regular probabilities for the TCAS branches. When we reach the top event we will have the probability of an NMAC with TCAS relative to the current probability of an NMAC.

To account for the range of conditions over which TCAS must operate, we use weighted averages for those conditions found in Section 3. For example, calculation of the effects of altimetry error takes into account the fraction of aircraft involved in NMACs that have high quality altimetry (assumed to be all air carrier and military aircraft, 21 percent) and the fraction that have the basic, or uncorrected altimetry (assumed to be all GA and other aircraft, 79 percent). Likewise, in Section 3 good conditions for visual acquisition of other aircraft (bright daylight) were found to exist for 70 percent of the incidents, so this will be used when visual acquisition is of importance. Other conditions include glaring sun, night, dusk, dawn, overcast, etc; for the analysis, these are arbitrarily assumed to be inadequate for visual acquisition.

Similar methods were used for estimation of other probabilities; as a consequence, the failure probabilities generated are failure rates over the entire airspace, with factoring already done to weight the probability of being in any given airspace. The failure rates are thus intended to assess the overall impact of TCAS, and not to predict its performance under any particular situation.

### 7.2.2 Summary of Failure Probabilities

Table 7-1 is a restatement of the basic probabilities obtained from Sections 3, 4, 5, and 6. From this data the failure rates of various events in the fault tree can be obtained; this is

TABLE 7-1
SUMMARY OF BASIC PROBABILITIES

| ITEM | CONDITION PRESENT | PROBABILITY | SECTION REFERENCE |
|---|---|---|---|
| a | Instrument Meteorological Conditions | .16 | 3.1.2 |
| b | Bright Daylight Conditions | .70 | 3.1.2 |
| c | GA and "other" Aircraft | .79 | 3.1.3 |
| d | Intruder is Transponder Equipped | .92 | 3.1.4 |
| e | Intruder is Mode C Transponder Equipped | .61 | 3.1.4 |
| f | Risk Ratio for GA Altimetry | .0317 | 4.2.4 |
| g | Unresolved Component | .0143 | |
| h | Induced Component | .0174 | |
| i | Risk Ratio for Maneuvering Intruder | .027 | 4.3.6 |
| | Probability of not being tracked | | |
| j | at time of TA | .06 | 5.1.2 |
| k | at time of RA | .03 | 5.1.2 |
| ℓ | Risk Ratio for "Stuck C-Bit" | .002 | 5.2.4 |
| m | Risk Ratio for Equipment Failure | .0001 | 5.3 |
| | Probability of not visually acquiring in bright daylight conditions | | |
| n | by 15 s before CPA | .17 | 6.7 |
| o | by time of RA | .35 | 6.7 |

shown in Table 7-2. The first column describes the event or failure; major failures are assigned numbers, while components of those failures are assigned letter identifiers. The event number associated with the failure occurrence is listed in column 2, and the event's probability is listed in column 3. The way these failure probabilities are derived from Table 7-1 is indicated in column 4.

### 7.2.3 Human Factors

There is no data base from which to assign nominal failure rates to human factors failures. These human factors are important, however, and thus we will use several variable quantities to indicate human-factor failure rates. They will be replaced by numerical quantities in the sensitivity analysis of Section 8. These account for the use of visual acquisition, the use of the Traffic Advisory, and the use of the Resolution Advisory. In turn, these may be broken down further depending upon whether an action is taken or not taken.

- Visual Acquisition (V). Upon visual acquisition, as aided by TCAS, it is expected that the pilot will be able to avoid an NMAC. However, this might fail in one of two ways:

    - VNA: The pilot visually acquires the threat, but does Not Avoid the NMAC (Events 7-396 and 7-392).

TABLE 7-2
SUMMARY OF FAILURE PROBABILITIES USED IN FAULT TREE QUANTIZATION

| DESCRIPTION OF EVENT | EVENT NO. | PROBABILITY | ITEMS FROM TABLE 7-1 |
|---|---|---|---|
| <u>000 BRANCH</u> | | | |
| 1. No TA is displayed | 6-375 | .43 | 1-e(1-j) |
| 1.a. Encounter is with non-Mode C aircraft | 376.211111 | .39 | 1-e |
| 1.b. Surveillance fails to acquire aircraft | 376.211112 | .06 | j |
| 2. Inadequate visual conditions | 7-386 | .30 | 1-b |
| 2.a. IMC | | .16 | a |
| 3. *Pilot does not visually acquire aircraft* (in good VMC with TA aid) | | | |
| 3.a. In time to avoid NMAC (15s before CPA) | 7-391 | .17 | n |
| 3.b. Prior to RA | | .35 | o |
| 4. No RA is displayed | 5-420 | .41 | 1-e(1-k) |
| 4.a. Encounter is with non-Mode C aircraft | 420.211111 | .39 | 1-e |
| 4.b. Surveillance fails to acquire aircraft | 420.211112 | .03 | k |
| 5. Inadequate RA is displayed | 5-450 | .011 | c g |
| <u>500 BRANCH</u> | | | |
| 6. TCAS displays RA which will lead to NMAC | 6-670 | | |
| 6.a. Altimetry error* | | .0081 | c h e(1-k) |
| 6.b. Intruder maneuvers* | | .016 | i e (1-k) |
| 6.c *C-Bit Errors** | | .001 | [illegible] e (1-k) |
| 7. No TA was displayed (on time) given that RA is displayed (7-670) | 9-688 | .03 | 1-(1-k)/(1-j) |
| 8. TA was displayed (on time) given that RA is displayed | 9-692 | .97 | (1-k)/(1-j) |
| <u>TOP EVENT</u> | | | |
| 9. Risk of Critical NMAC (Section 4.3.3) | (multiplies top event) | $1 \times 10^{-5}$ /hr | |

* Assumes 61% of encounters are with Mode C aircraft, 97% surveillance acquisition rate.

- VMIR: The pilot visually acquires the threat but still Maneuvers on an Incorrect Resolution Advisory (Event 8-796).

- Resolution Advisory (R): Expedient action, at least compatible with the RA, is necessary. Various factors may inhibit the pilot's reaction thereby failing to avoid an NMAC. This leads to the following failure:

  - RNF: The pilot does Not Follow the RA (Event 5-440).

- Traffic Advisory (T): The intent of the TA is to alert the pilot to search for the intruder. If visual acquisition is not achieved and action is taken on the TA alone, failure may occur in one of two ways:

  - TNA: Based on his interpretation of the TA, the pilot disregards an RA or what he sees and does Not Avoid the NMAC.

  - TI: The pilot maneuvers to Induce an NMAC based on his interpretation of the TA.

These five failure mechanisms (represented by the variables VNA, VMIR, RNF, TNA, and TI) will be treated in the quantitative analysis of the fault tree.

### 7.3 Reduction and Evaluation of the Fault Tree

The evaluation of the fault tree is simplified if a nominal, or baseline, set of operational conditions is assumed. Variations from these nominal conditions can then be explored in a subsequent analysis of the sensitivity to these assumptions. The assumed nominal conditions are:

1. If a pilot visually acquires a conflicting aircraft, he will avoid it.

2. In absence of visual acquisition, the pilot follows the Resolution Advisory.

3. Visual acquisition, as aided by the Traffic Advisory display for Mode C aircraft, is assumed to be effective only in bright daylight.

4. The airborne traffic has today's level of transponder and Mode C equipage.

5. The intruder is not TCAS-equipped. (If the intruder were TCAS-equipped, it would have air carrier quality altimetry, and its displayed escape maneuver would be coordinated.)

6. No "false moves" are made by the TCAS pilot either from confusion or from prematurely maneuvering based on a Traffic Advisory.

7. Today's level of vigilance for see-and-avoid procedures is maintained; that is, TCAS does not cause the pilot to relax his guard.

A second simplification occurs because we are computing the <u>relative</u> probability of an NMAC. We first identify all non-TCAS branches and assign probabilities of 1.0 or 0.0 to them; this will substantially reduce the size of the tree for analysis. We can then compute the probabilities at the remaining gates from the bottom up. The 000 Branch of the tree, Unresolved NMAC, will be reduced and evaluated first, followed by the 500 Branch of the tree, Induced NMAC.

### 7.3.1 Branch 000 of the Fault Tree, Unresolved NMAC

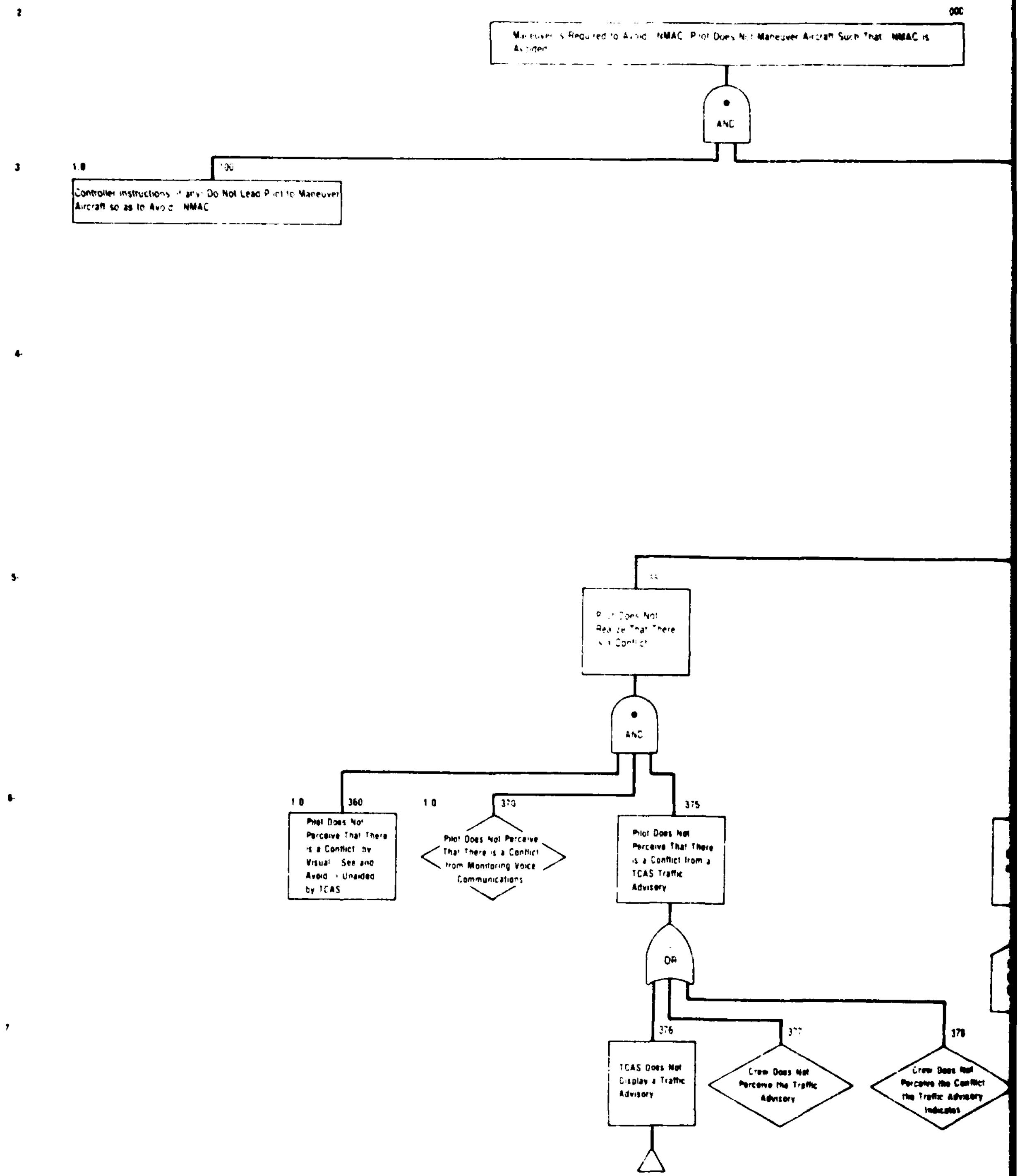
#### 7.3.1.1 Reduction of 000 Branch

For computation of relative risk, we have reduced the 000 branch of the fault tree that was shown in Figure 7-2 to the form shown in Figure 7-4. It contains branches for controller faults (event 3-100), pilot faults (many of the branches under event 4-350), and TCAS faults (some of the branches under event 4-350 and the branch under event 4-410). For computation of relative risk, we have reduced it as follows.

Controller Faults: Branch 100

Controller faults enter the tree in the branch under event 3-100, combining with the pilot-TCAS branch (3-300) at an AND gate. The controller faults are independent of pilot faults; the introduction of TCAS provides some common cause failures (in particular, with conflict alert), but it will be assumed their effect on the independence between events 3-100 and 3-300 is negligible.

We will assign a failure rate of 1.0 to event 3-100. (A failure is presumed to have already occurred, or the pre-existing NMAC would not be in process.) Since we are assuming independence between events 3-100 and 3-300, this will multiply with the failure rate of event 3-300. The

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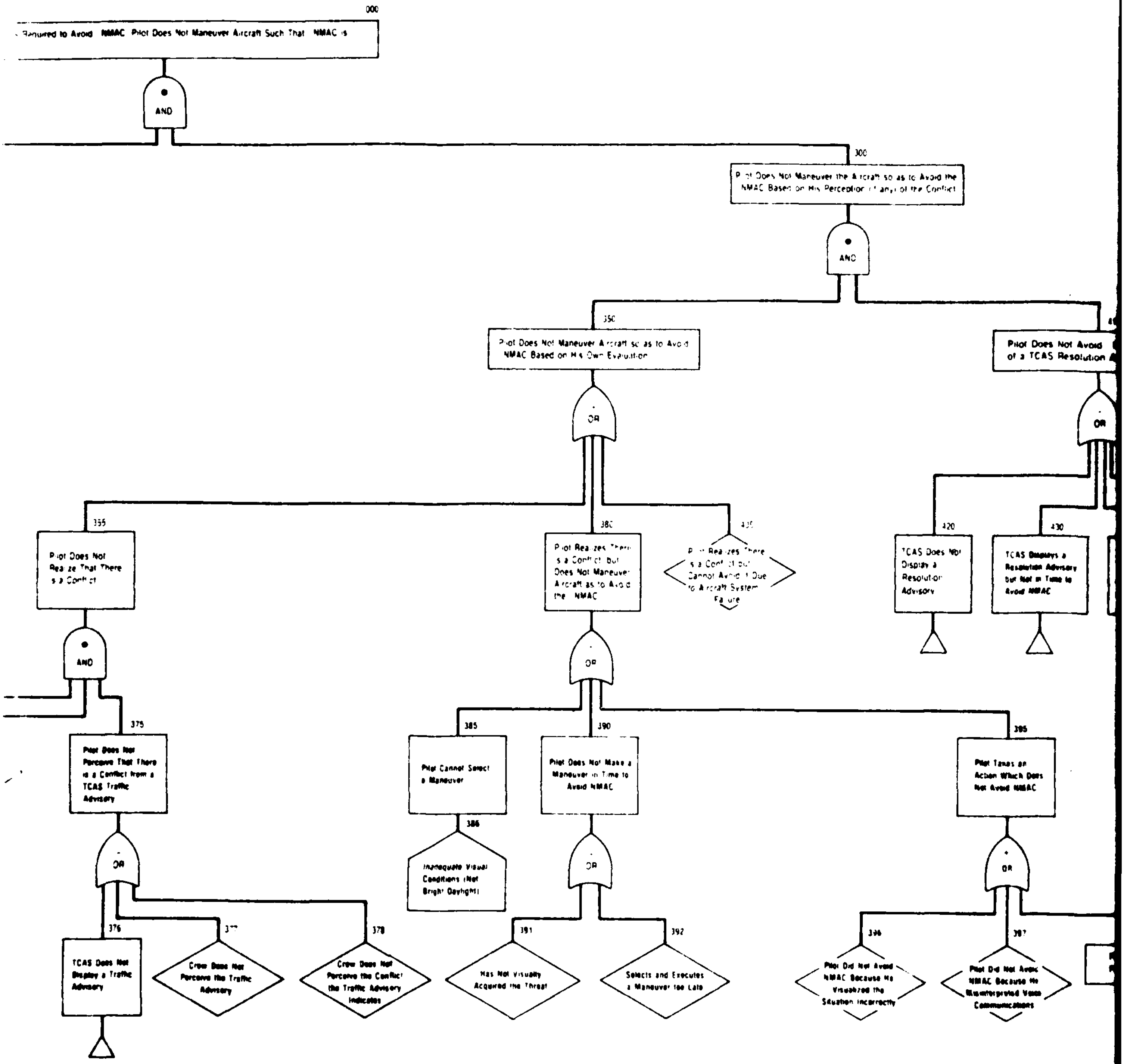


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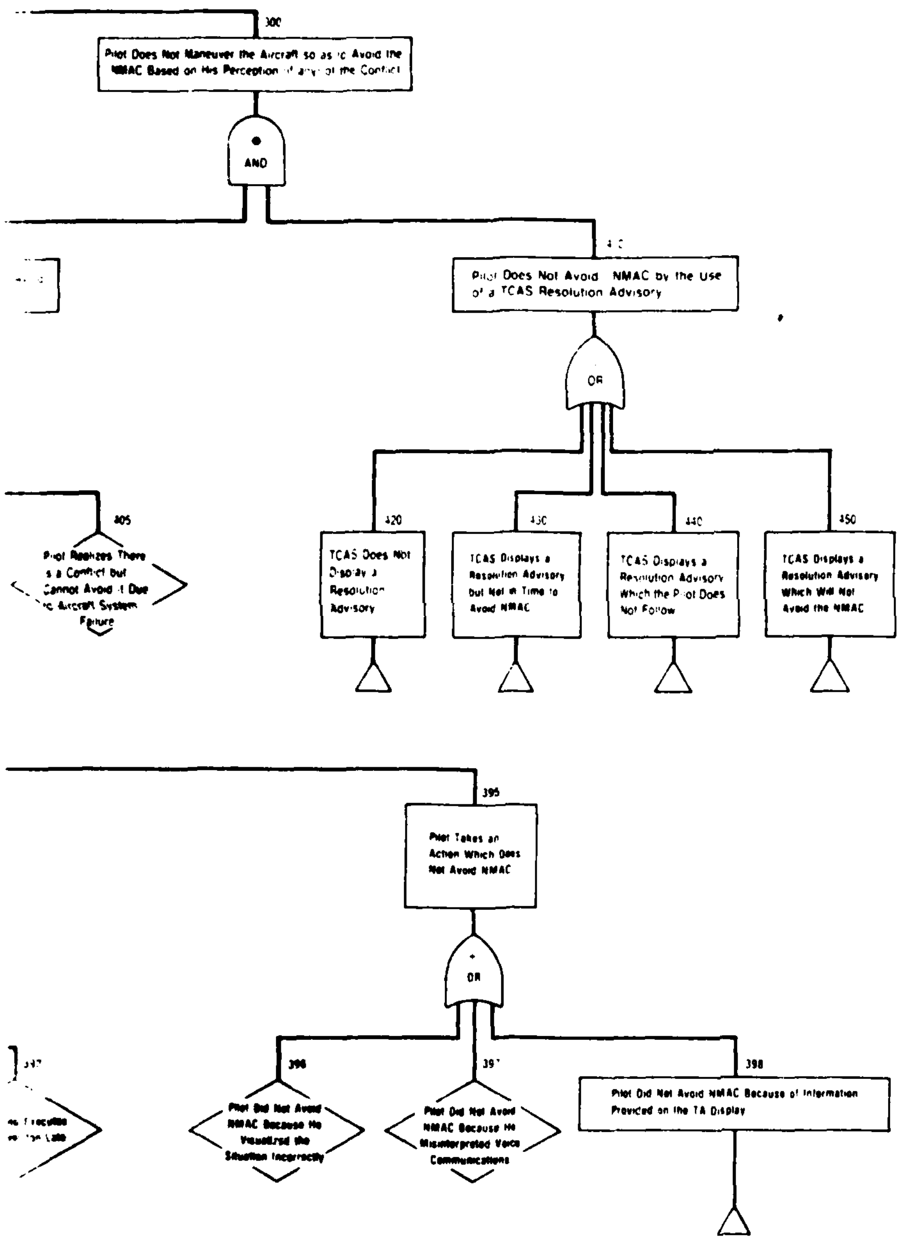


**FIGURE 7-4**
**000 BRANCH OF FAULT TREE REDUCED FOR ANALYSIS**



3

probability of an unresolved critical NMAC (event 000) then becomes the same as the probability that the pilot does not maneuver the aircraft based on his information (event 3-300). This is consistent with assumptions that there are no interactions between the controller and the pilot using TCAS.

Pilot Faults: Branch 350

Pilot faults enter the tree in the branch under event 4-350; these combine with the faults for TCAS Resolution Advisories, event 4-410. TCAS Traffic Advisory faults appear under the pilot branch because a Traffic Advisory is an aid to visual acquisition of a threat and thus changes pilot failure rates for visual acquisition.

In the course of analysis, we are going to assume that pilot's unaided visual acquisition (event 6-360) and perception of conflict from communications (event 6-370) have already failed and thus assign them failure rates of 1.0. All other branches of the fault tree constitute TCAS-related faults or relate to environmental conditions in which TCAS will operate; these branches will have an effect on the computation of relative risk.

7.3.1.2 Evaluation of 000 Branch

Figure 7-4 shows the operational events and, by implication, the environmental features which can constitute a certain class of fault mechanisms for TCAS. Certain interpendencies exist which are not explicitly defined within the structure but must be taken into account. Where this occurs, must look down to the subevents below the event being evaluated to insure that common causes and operational requirements are treated correctly. We evaluate these events by calculating the joint



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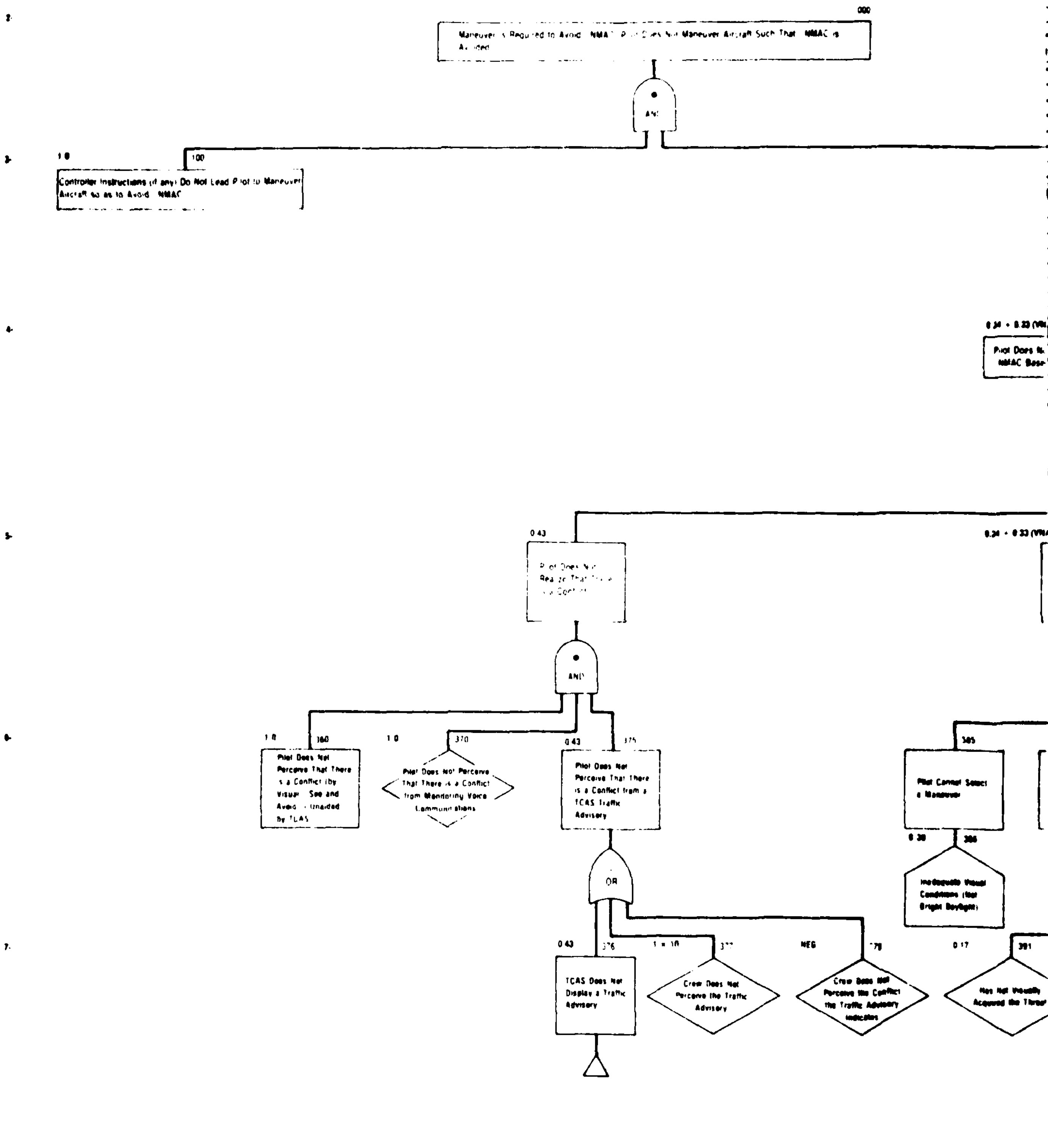
probabilities of <u>all</u> subevents at a level below which no interdependence exists. For branch 000 of the fault tree, that level is approximately the bottom level depicted in Figure 7-4.

One can go through the process of calculating the joint probabilities for each event in the tree; this process is performed in Appendix G and the results brought forward for events 4-350 and 4-410 in Figure 7-5. The failure rate for event 3-300 will be developed here.

<u>Estimation of Event 3-300, Failure of Pilot to Avoid NMAC with the Aid of TCAS</u>

As events 4-350 and 4-410 are not independent, the probabilities do not multiply to generate the probability of event 3-300. Instead, the common causes of failures for both 4-350 and 4-410 must be identified and the analysis performed to recognize the common failures. In particular, there are major common cause failures for Traffic Advisories and Resolution Advisories. Non-transponder aircraft cause both TA and RA "failure"; surveillance failure often causes both TA and RA failure. We must calculate the joint probabilities of these events in order to accurately calculate the total failure rate for event 3-300.

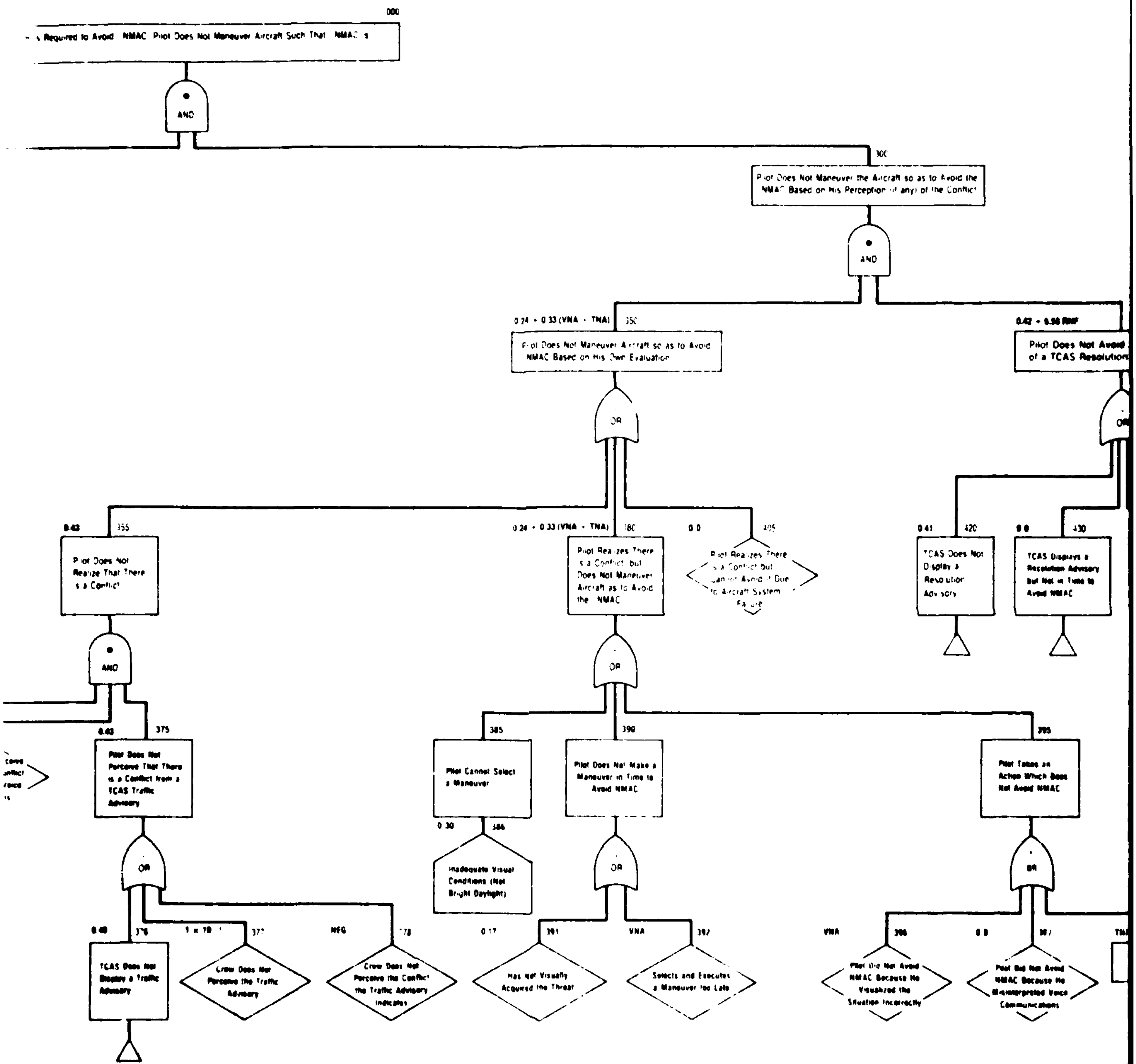
Figure 7-6 illustrates how this probability is calculated. The diagram (NOT to scale) first breaks up all current NMAC encounters (1.0 or 100 percent) into those in which a TA is displayed and those in which one is not displayed. Some of the probabilities are obtained directly from Table 7-2; others will be derived after a discussion of the meaning of the figure. If a TA is not displayed, TCAS does not improve the inherent visual acquisition of the pilot. If, in addition, no RA is



000
Maneuver is Required to Avoid NMAC; Pilot Does Not Maneuver Aircraft Such That NMAC is Avoided
AND
1.0
100
Controller Instructions (if any) Do Not Lead Pilot to Maneuver Aircraft so as to Avoid NMAC
Pilot Does Not Realize That There is a Conflict
0.43
AND
Pilot Does Not Perceive That There is a Conflict (by Visual See and Avoid) Unaided by TCAS
360
370
Pilot Does Not Perceive That There is a Conflict from Monitoring Voice Communications
0.43
375
Pilot Does Not Perceive That There is a Conflict from a TCAS Traffic Advisory
OR
0.43
376
TCAS Does Not Display a Traffic Advisory
Crew Does Not Perceive the Traffic Advisory
NEG
Crew Does Not Perceive the Conflict the Traffic Advisory Indicates
385
Pilot Cannot Select a Maneuver
386
Inadequate Visual Conditions (Not Bright Daylight)
0.17
391
Has Not Visually Acquired the Threat




1



000
Pilot Does Not Maneuver Aircraft Such That NMAC Is
AND
300
Pilot Does Not Maneuver the Aircraft so as to Avoid the NMAC Based on His Perception (if any) of the Conflict
AND
0.24 + 0.33 (VNA + TNA)
350
Pilot Does Not Maneuver Aircraft so as to Avoid NMAC Based on His Own Evaluation
0.42 + 0.58 RMF
Pilot Does Not Avoid
of a TCAS Resolution
OR
OR
0.43
355
Pilot Does Not Realize That There is a Conflict
0.24 + 0.33 (VNA + TNA)
380
Pilot Realizes There is a Conflict but Does Not Maneuver Aircraft as to Avoid the NMAC
0.0
405
Pilot Realizes There is a Conflict but Cannot Avoid It Due to Aircraft System Failure
0.41
420
TCAS Does Not Display a Resolution Advisory
0.0
430
TCAS Displays a Resolution Advisory but Not in Time to Avoid NMAC
AND
OR
0.43
375
Pilot Does Not Perceive That There is a Conflict from a TCAS Traffic Advisory
385
Pilot Cannot Select a Maneuver
390
Pilot Does Not Make a Maneuver in Time to Avoid NMAC
395
Pilot Takes an Action Which Does Not Avoid NMAC
0.30
386
Inadequate Visual Conditions (Not Bright Daylight)
OR
OR
OR
0.40
376
TCAS Does Not Display a Traffic Advisory
NEG
Crew Does Not Perceive the Traffic Advisory
Crew Does Not Perceive the Conflict the Traffic Advisory Indicates
0.17
391
Has Not Visually Acquired the Threat
VNA
392
Selects and Executes a Maneuver Too Late
VNA
396
Pilot Did Not Avoid NMAC Because He Visualized the Situation Incorrectly
0.0
Pilot Did Not Avoid NMAC Because He Misinterpreted Voice Communications


②

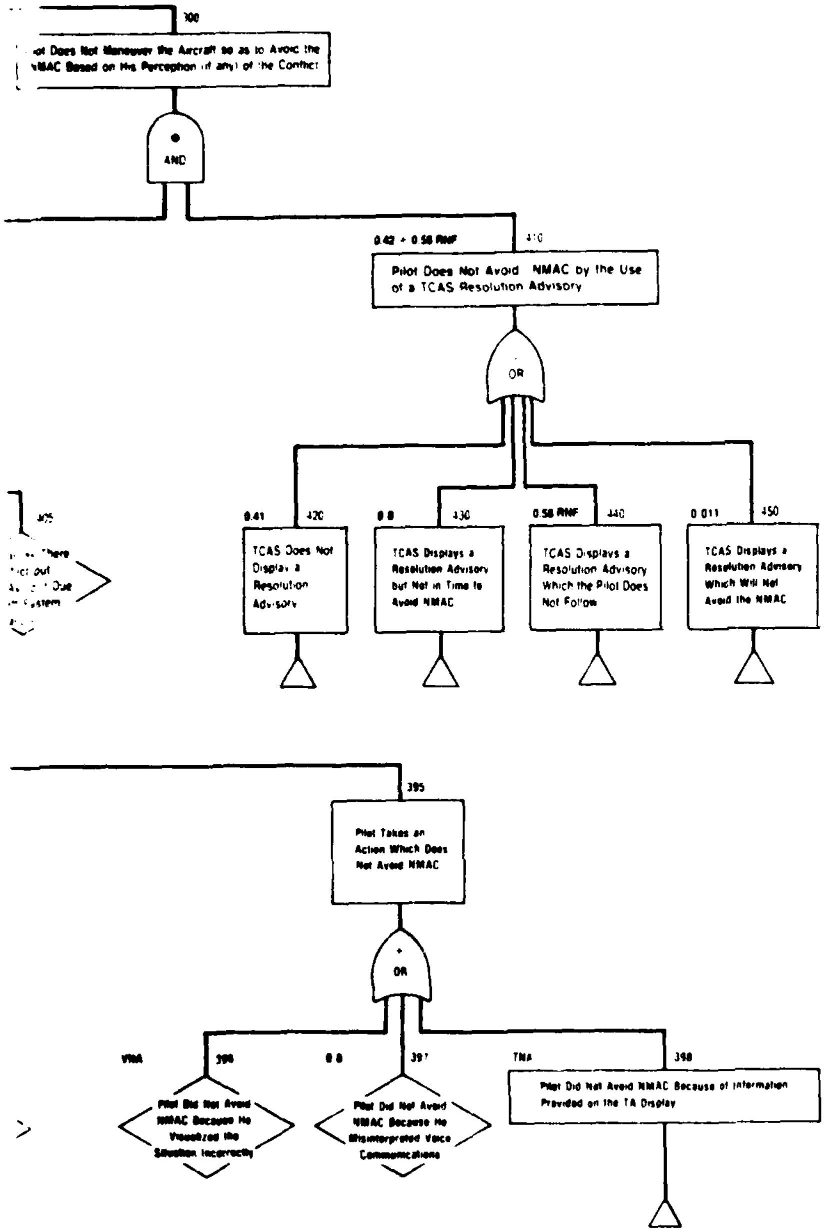



**FIGURE 7-5**
**QUANTITATIVE FAULT TREE ANALYSIS**
**RESULTS BELOW EVENT 3-300**

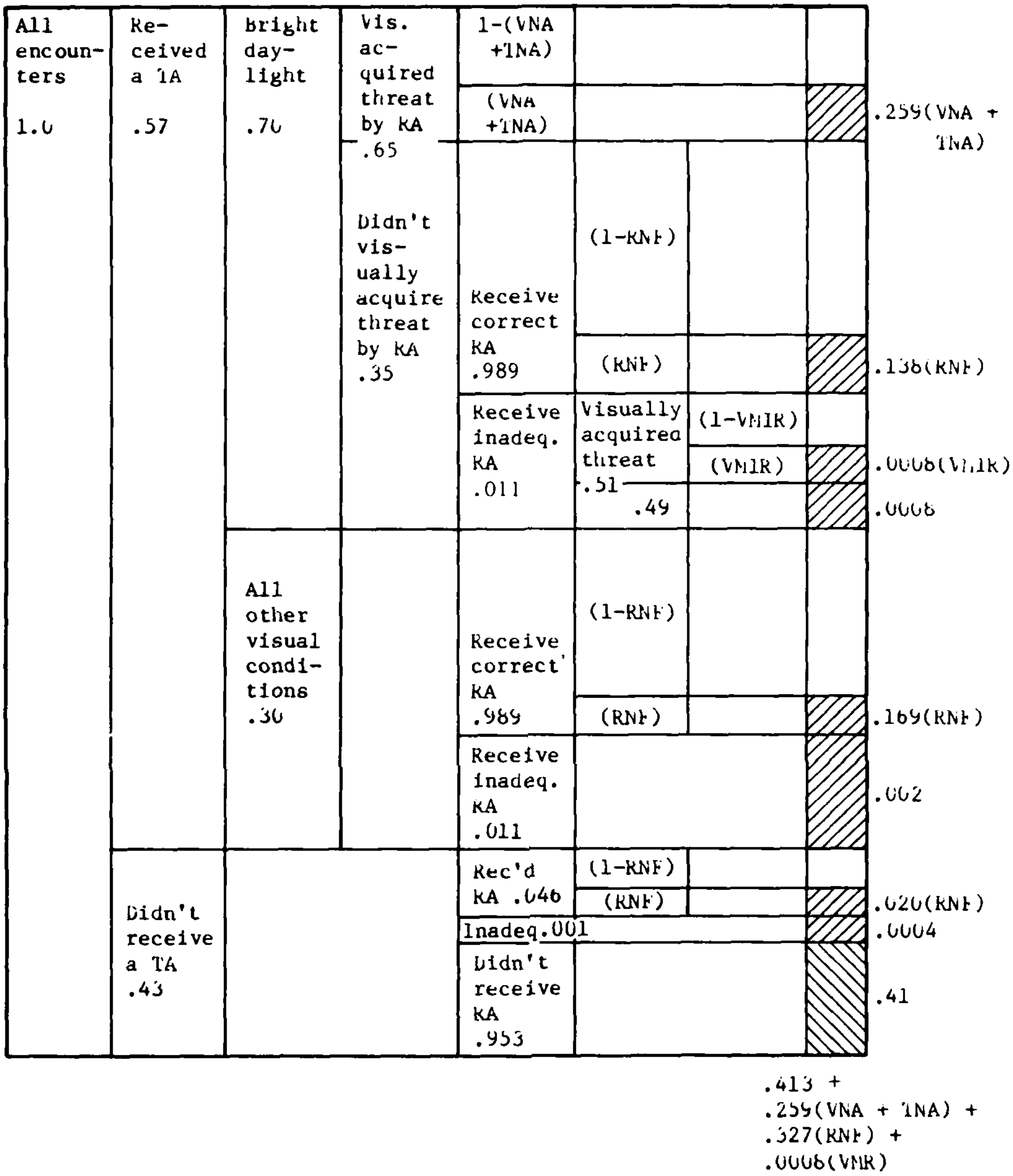



**FIGURE 7-6**
**CALCULATION OF THE PROBABILITY OF EVENT 3-300**



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received, these encounters will contribute to the failure probability of event 3-300, as indicated by the shading in the last column of the bottom row. The probability of this occurrence is shown to the right of the shaded column.

Two processes are at work here: a see-and-avoid process (4-350) and a process of following a displayed RA (4-410). We assume that, if the pilot visually acquires the aircraft before an RA is issued (top row of Figure 7-6), he can avoid the aircraft in all but (VNA + TNA) of the encounters, regardless of whether an adequate RA is displayed. Should the pilot not visually acquire the aircraft before the time of the RA, he follows it in all but RNF of the encounters (if one is displayed) while continuing to try to visually acquire the threat. In some instances, the RA may not generate adequate separation; if the pilot visually acquires the threat, it is assumed he can determine that this is the case and take an alternate action in all but VMIR of the encounters.

The probabilities listed in Figure 7-6 are derived from Table 7-2. Those requiring derivation are described as follows:

- A failure to display the RA, given there was no preceding TA, can arise as follows: (1) the threat had no Mode C transponder; or (2) poor surveillance throughout the encounter. We know the probability over all encounters of these two occurrences. The probability of encountering a non-transponder aircraft, from 1.a. in Table 7-2, is .39. (This is the principal failure mode for TCAS in today's environment.) The probability of surveillance not acquiring the threat in time for the TA is .06, and in time for the RA, .03; the .03 is contained in the .06 (the two are not independent), so the probability of no TA and no RA, due to surveillance, is .06 - .03 = .03. The set union of these two occurrences provides the failure rate for the scenario wherein neither a TA nor RA is received, .41. (The failure rate for no RA given no TA, .953, is provided for completeness.)

- The probability of visually acquiring an aircraft by 15 seconds prior to CPA, given that you have not acquired it by the time of the RA, is .51; this is obtained by noting that the probability of failing to acquire by 15 seconds prior to CPA is (1-.51) x .35 or .17, which matches the result 3.a. in Table 7-2.

- Given that you have received a TA, you will receive an RA with probability 1.0; it will be inadequate to avoid the NMAC with probability .011, because of altimetry error.

We can summarize the failure regions of Figure 7-6 which do not include human factors as follows:

- Encounters in which neither TA nor RA is received. This failure is primarily caused by lack of mode C equipage levels, and is the principal failure mode for TCAS. (Probability: .41)

- Bright daylight encounters in which a TA is received, visual acquisition does not occur and an inadequate RA is generated. (Probability: .0008)

- Encounters in which a TA is received, visual acquisition is not possible, and an inadequate RA is received. (Probability: .002)

- Encounters in which a TA is not received prior to the RA, an RA is generated, but it is inadequate to avoid the NMAC. (Probability: .0004)

In addition, there are failure regions of Figure 7-6 which relate to human factors as follows:

- Bright daylight encounters in which a TA is received and visual acquisition does occur before the RA, but the pilot fails to avoid the critical NMAC with probability VNA + TNA. (Probability: .259(VNA + TNA))

- Bright daylight encounters in which a TA is received visual acquisition does not occur, an RA is generated, but the pilot fails to follow the RA with probability RNF. (Probability = .138 RNF)

- Bright daylight encounters in which a TA is received, visual acquisition occurs but not before the RA is issued. An inadequate RA is issued, and the pilot acquires the threat, but does not determine the RA to be inadequate with probability VMIR. (Probability .0008 VMIR)

- Encounters in which a TA is received, visual acquisition is not possible, and the pilot does not follow the RA with probability RNF. (Probability .169 RNF)

- Encounters in which no TA is received, an RA is received but is not followed with probability RNF. (Probability = .020 RNF)

The total failure rate for event 3-300 is thus .413 + .259 (VNA + TNA) + .327 (RNF) + .0008 (VMIR); this becomes the failure rate for event 2-000, an unresolved NMAC.

### 7.3.2 Branch 500 of the Fault Tree, Induced NMAC

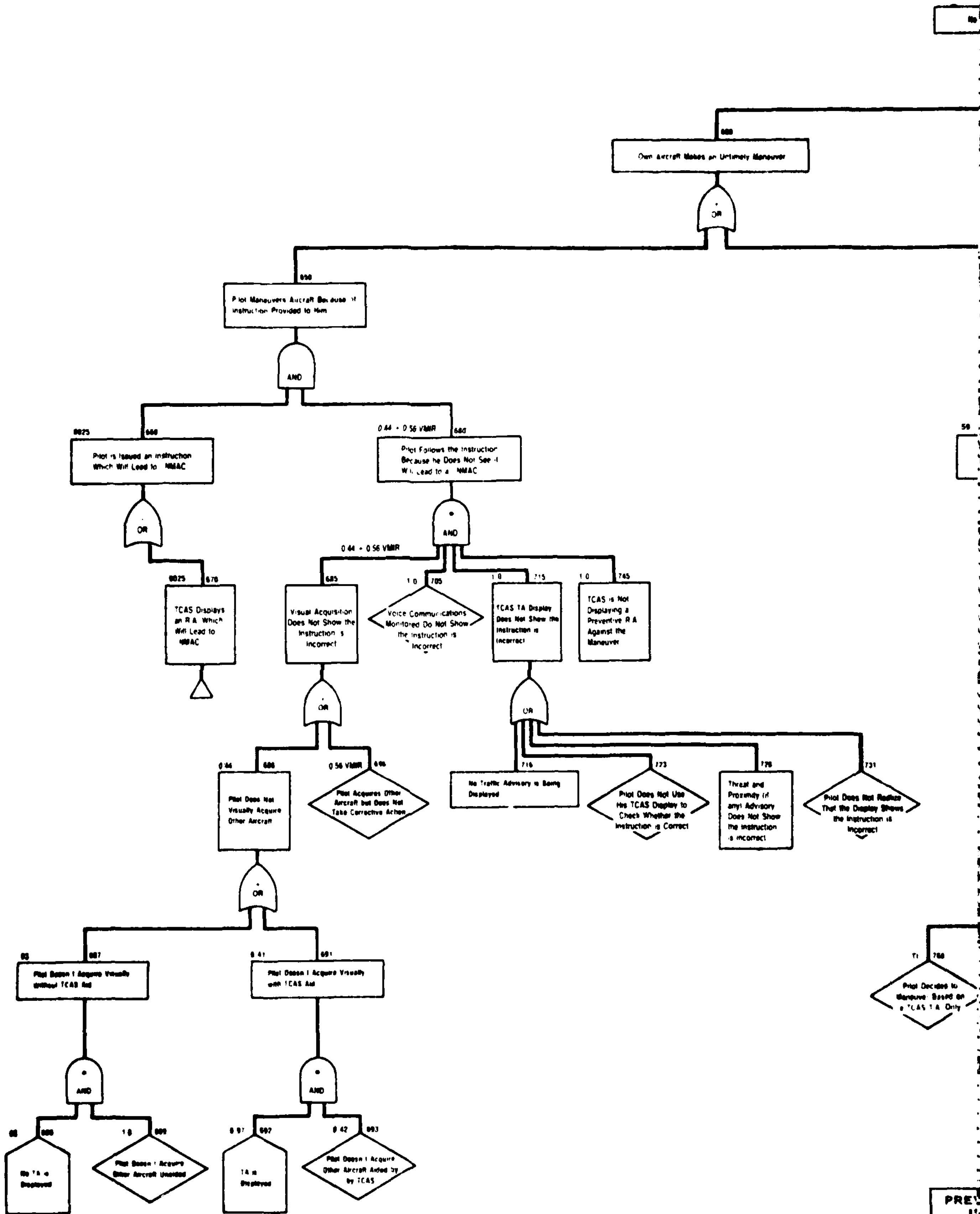
The 500 branch of the fault tree is the combination of several cases which could induce an NMAC, some of which TCAS provides protection against and some of which TCAS could cause. We are going to neglect those cases in which TCAS provides benefit, as they are not only difficult to evaluate, but they are not frequent occurrences. We will instead consider only the cases wherein TCAS induces a near-midair collision, either because of a Traffic Advisory or because of a Resolution Advisory.

#### 7.3.2.1 Reduction of Branch 500

The reduced 500 branch of the fault tree, Induced NMAC, is shown in Figure 7-7. It has been reduced by removing the branches for non-TCAS induced NMACs, as follows.

#### Traffic Advisories-Induced NMAC

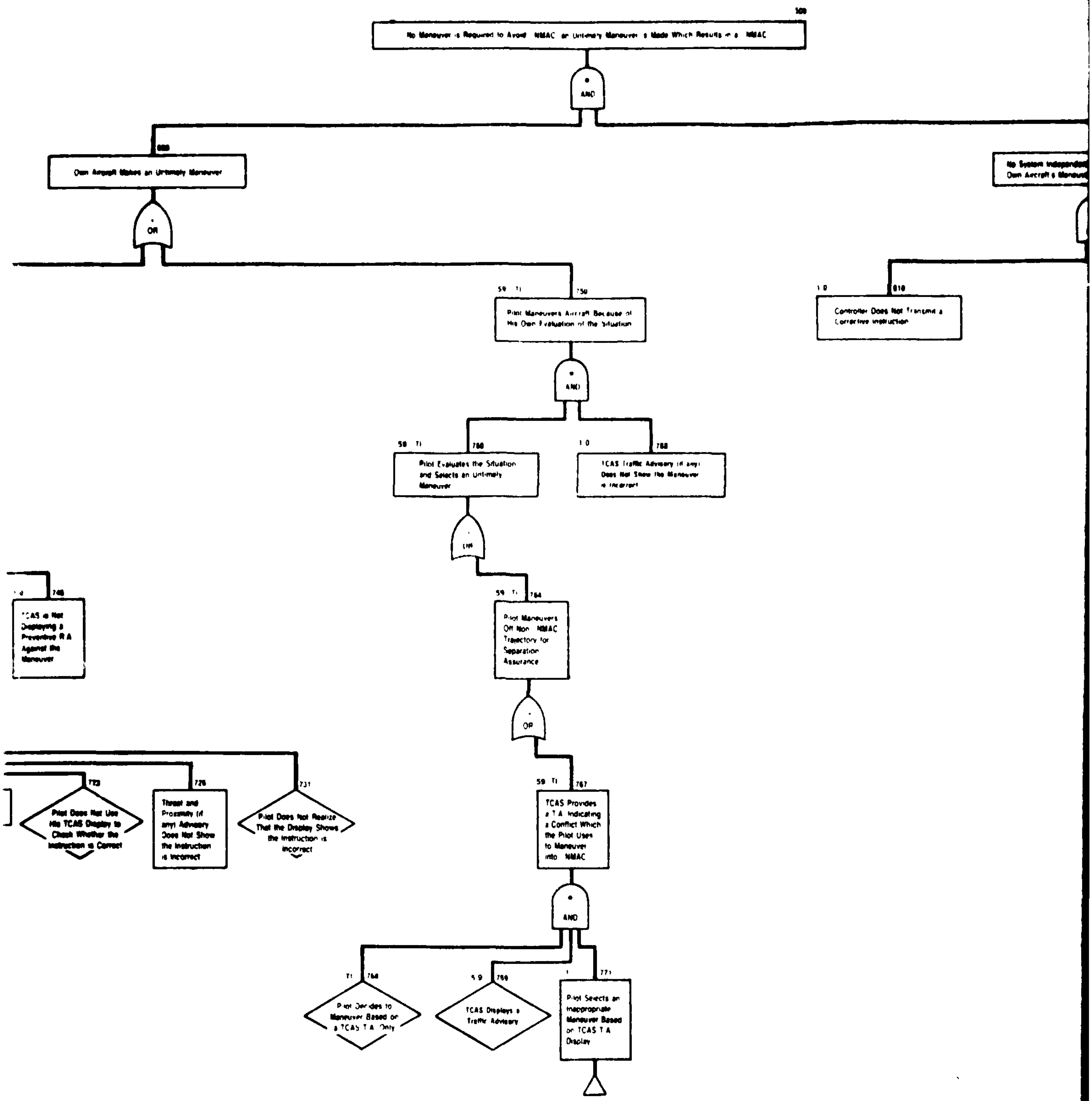
The possibility that the pilot might use a TA, not for visual acquisition, but as the basis for a maneuver which induces an NMAC (when one would not have occurred except for the maneuver)



Own Aircraft Makes an Untimely Maneuver
OR
Pilot Maneuvers Aircraft Because of Instruction Provided to Him
AND
Pilot is Issued an Instruction Which Will Lead to NMAC
0.44 + 0.56 VMIR
Pilot Follows the Instruction Because he Does Not See it Will Lead to a NMAC
OR
TCAS Displays an R.A. Which Will Lead to NMAC
AND
0.44 + 0.56 VMIR
Visual Acquisition Does Not Show the Instruction is Incorrect
Voice Communications Monitored Do Not Show the Instruction is Incorrect
TCAS TA Display Does Not Show the Instruction is Incorrect
TCAS is Not Displaying a Preventive R.A. Against the Maneuver
OR
OR
0.56 VMIR
Pilot Does Not Visually Acquire Other Aircraft
Pilot Acquires Other Aircraft but Does Not Take Corrective Action
No Traffic Advisory is Being Displayed
Pilot Does Not Use His TCAS Display to Check Whether the Instruction is Correct
Threat and Proximity (if any) Advisory Does Not Show the Instruction is Incorrect
Pilot Does Not Realize That the Display Shows the Instruction is Incorrect
OR
Pilot Doesn't Acquire Visually Without TCAS Aid
Pilot Doesn't Acquire Visually with TCAS Aid
AND
AND
No TA is Displayed
Pilot Doesn't Acquire Other Aircraft Unaided
TA is Displayed
Pilot Doesn't Acquire Other Aircraft Aided by TCAS
Pilot Decides to Maneuver Based on a TCAS TA Only




①

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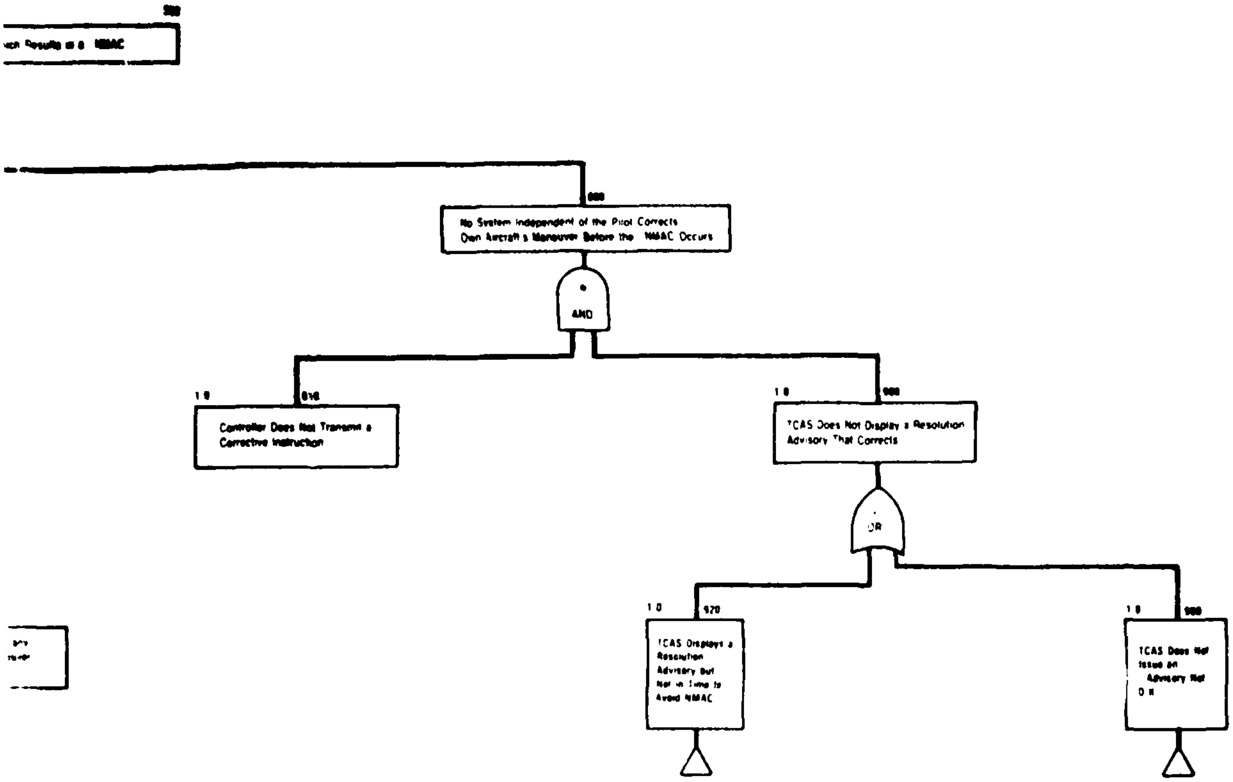


**FIGURE 7-7**
**500 BRANCH OF FAULT TREE**
**REDUCED FOR ANALYSIS**



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is represented by event 7-767. This is the only TCAS-related event under event 5-760 (Pilot Evaluates Situation and Selects Untimely Maneuver).

The probability of any event contained in branch 760 is affected by branch 780; that is, the TCAS TA indicating that the pilot should not make the selected maneuver. In this case, however, TCAS Traffic Advisory is not likely to provide an indication to the pilot that he should not choose that maneuver, since the pilot chose the maneuver based on the TA; we thus assign a failure rate of 1.0 to event 5-780.

The only other circumstances that could modify this probability rely on corrective instructions from the controller or from TCAS (by means of a Resolution Advisory) (events 4-810 and 4-900). Though noting this possibility, we will assign failure probabilities of 1.0 to events 4-810 and 4-900. Thus, the probability that the pilot uses a TA to maneuver into an NMAC will be taken as the probability of event 7-767 (TCAS Provides a TA Indicating a Conflict Which the Pilot Uses to Maneuver Into an NMAC).

Resolution Advisory-Induced NMAC

The event of a Resolution Advisory-induced NMAC, event 6-670, is the only TCAS-related component of event 5-660. The likelihood that this will lead to a critical NMAC can be modified by only two other branches.

The first branch is event 5-680 (Pilot Follows the Instruction Because He Does Not See It Will Lead to an NMAC) and below. There are four basic factors which could cause the pilot to perceive that the RA is incorrect. Voice communications (event



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7-705) are assumed not to provide any reason not to take the RA, and thus event 7-705 is assigned a failure rate of 1.0. Given that an RA has been issued which will lead to an NMAC, the TA (event 7-715) is not likely to indicate anything wrong with it and is assigned a failure rate of 1.0, and since it is an RA that has been issued, no preventive RA is going to be in existence (event 7-745), so we assign it a failure rate of 1.0.

This leaves only event 6-685, visual acquisition, to override any incorrect RA. The failure rate will have two components; these are represented by event 7-686, the pilot's failure to acquire the threat, and event 7-696, the failure to avoid the threat once the pilot has acquired it.

The one remaining branch that can affect the probability that the RA will lead to an NMAC is the one under event 3-800, which in turn is composed of a controller branch (event 4-810) and a TCAS branch (4-900). The controller's effect will be neglected and assigned a failure rate of 1.0. In addition, TCAS effect will also be neglected and assigned the 1.0 failure rate, even though it includes a branch that measures the effect of an "advisory not O.K." This means that the probability of event 4-650, Pilot Maneuvers Aircraft Because of Instruction Provided to Him (the instruction in this case being an incorrect RA), is the probability that an RA leads to an NMAC.

#### 7.3.2.2 Evaluation of the 500 Branch

The probability of the lower level events have been calculated and are shown in Figure 7-7. When calculating the probability of event 4-650, one must take into account that branches 5-660 and 5-680 are interdependent, so the analysis to obtain the

the probability of event 4-650 must be done, as follows, in a mannner similar to that of event 3-300 in branch 000 of the tree. The result must then be summed to the probability of event 7-767 to obtain the probability of event 2-500 (induced NMAC).

Estimation of Event 4-650

The method by which the probability of event 4-650 was calculated is illustrated in Figure 7-8. There are two probabilities assigned to the scenarios from Table 7-2 which are derived as follows:

- The occurrence of an encounter in which an incorrect RA (one that would induce a critical NMAC if followed) is received is the set union of the events associated with failure rates 6.a, 6.b., and 6.c. from Table 7-2. No other source is judged to be significant. (See Appendix E for logic verification and Section 5.3, equipment reliability). Recall from Sections 4.1.5, 4.2.4, and 5.2.4 that the probabilities of these occurrences were higher; however, those analyses assumed an encounter between two Mode C aircraft and that surveillance had acquired the aircraft. Thus, to obtain the probability that an induced NMAC occurs in the TCAS environment, we must multiply the probabilities from those analyses by the probability of encountering a Mode C aircraft (.61), and by the probability of surveillance acquiring the other aircraft (.97) to obtain the probabilities shown in Table 7-2.

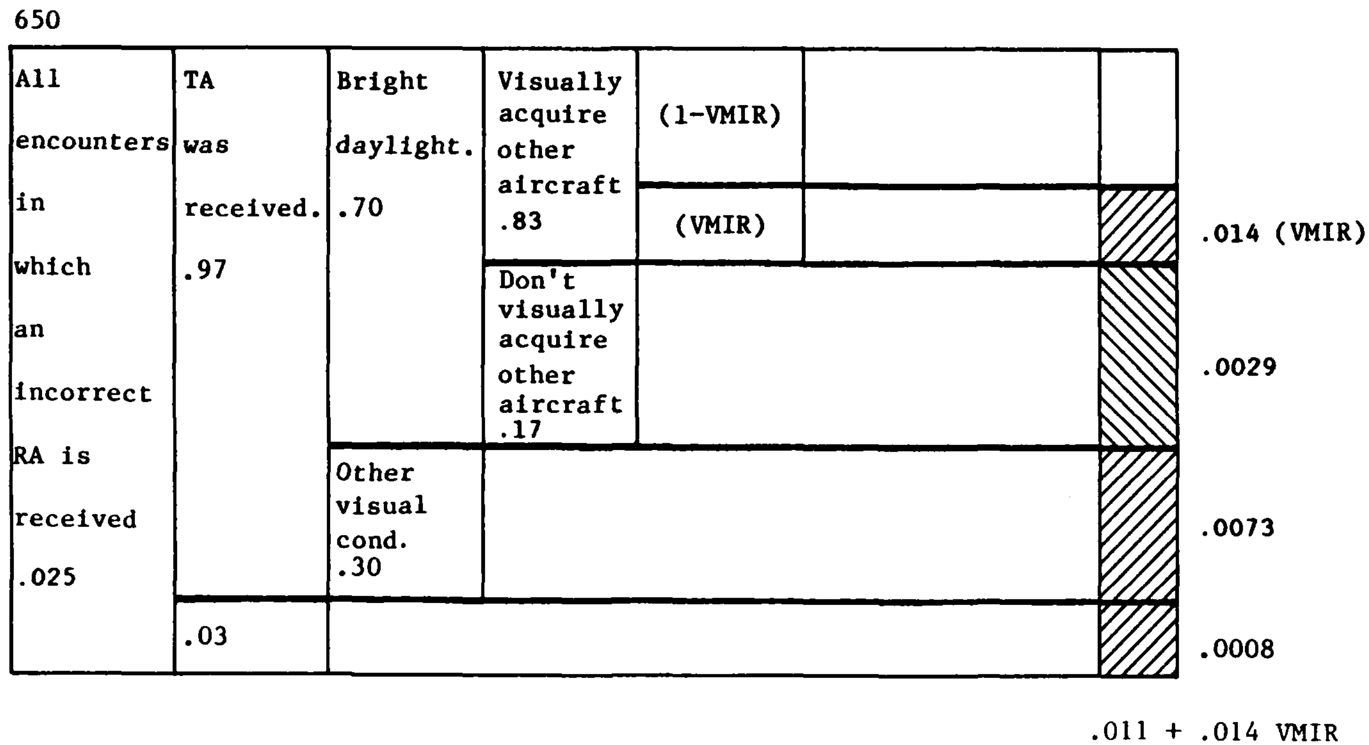



**FIGURE 7-8**
**CALCULATION OF THE PROBABILITY OF EVENT 4-650**

- The probability a TA was received. Since an RA was received, this is a conditional probability of receiving a TA, given the existence of an RA. This probability is .97 and is obtained as follows: there is only one failure mechanism by which one can receive an RA without having received the TA on time -- surveillance failure causing the TA not to be received on time, but no surveillance failure at the time of the RA. Thus, we divide the success rate for a timely TA, .94, by the success rate for a timely RA, .97, to obtain the success rate for a TA given the existence of an RA, or .97.

The failure scenarios for this event with their associated probabilities are:

- Encounters in which visual acquisition occurs but the pilot does not see that the RA is incorrect with probability VMIR. (Probability: .014 VMIR)

- Encounters in which a TA is received and visual acquisition is possible, but fails to occur. (Probability .0029)

- Encounters in which a TA is received, but visual acquisition is not possible. (Probability: .0073)

- Encounters in which a TA is not received. (Probability: 0.0008)

The sum of these probabilities, .011 + .014 VMIR, is the probability that the pilot will follow an incorrect RA.

Estimation of Event 7-767

The probability that a Traffic Advisory induces an NMAC is the probability of the joint occurrence of three events: That a TA is displayed, that the pilot maneuvers on the basis of that TA, and that the maneuver induces an NMAC. The derivation of each probability, as listed in the tree in Figure 7-7, is as follows:

- Pilot Decides to Maneuver Based on a TCAS TA Only (event 8-768). This has been assigned the Variable TI, which was described earlier.

- TCAS Displays a Traffic Advisory (event 8-769). If every aircraft were Mode-C equipped and surveillance had a 100% acquisition rate, TCAS would display a TA on every proximate aircraft. The number of proximate aircraft is approximately 10 times the number of current NMACs; however, since only 61 percent of these proximate aircraft will be Mode-C equipped and surveillance will only acquire 97 percent of them, the number of TAs displayed for these aircraft will be .61 x .97 x 10 or 5.9, as shown above event 8-769. The significance of this is that a number of proximate encounters equal to 5.9 times the number of NMACs in today's environment will display a TA that could lead to an induced NMAC, if all conditions were unfavorable.

- Pilot Selects an Inappropriate Maneuver Based on the TCAS TA Display (event 8-771). We have assumed a random model of pilot maneuvers in the vertical dimension, which does not utilize any of the information presented in the TA display and which totally neglects any information obtained by visual acquisition and/or a Resolution Advisory. We will assume that, on receipt of the TA, the pilot maneuvers to another altitude within ± 1000 feet of his original altitude. As proximate encounters are uniformly distributed in the vertical dimension, there is a 0.1 probability that the intruder passes within ± 100 feet of the altitude the pilot maneuvers to ((100 feet above + 100 feet below)/(1000 feet above + 1000 feet below)).

These three probabilities multiply to produce the probability (.59 TI) that a vertical maneuver by the pilot based on the TA induces an NMAC. This result is conservative in several respects: 1) it assumes the pilot does not make a horizontal maneuver which could avoid the NMAC; 2) it assumes that the pilot does not use correct information provided to make a safe maneuver, but instead moves in a random manner.

This probability is summed with the probability of event 4-650 to obtain the probability of event 3-600. Since we assumed the probability of event 3-800 to be 1.0, the sum carries to the top of the tree. The probability of event 2-500 is thus .011 + .014 VMIR + .59 TI.

### 7.4 Summary of Results

The probabilities calculated for events 2-000 and 2-500 are brought forward in Figure 7-9. As these two events are mutually exclusive, we can sum the two probabilities to obtain

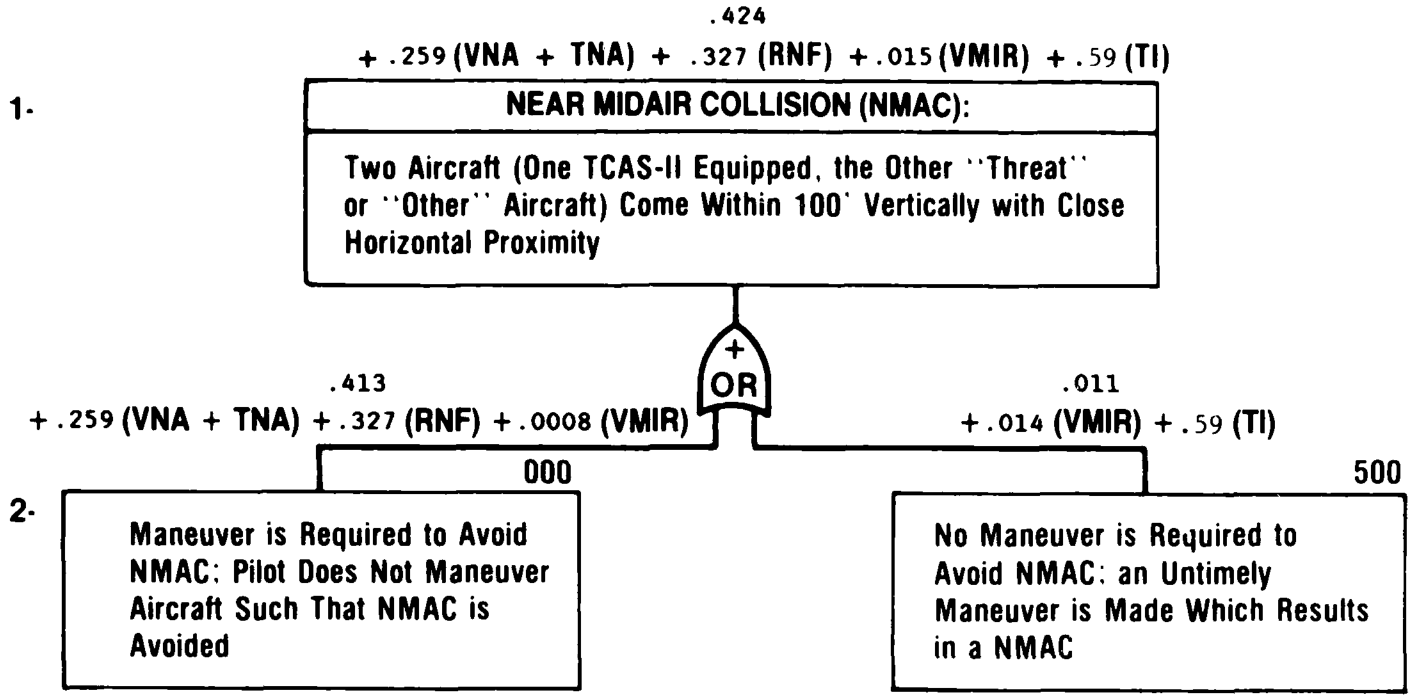



FIGURE 7-9
CALCULATION OF THE PROBABILITY OF TOP EVENT

the probability of a critical near midair collision, which is .424 plus a residual composed of human factors failures.

Aside from the human factors components, one result stands out: of the .424 probability, approximately .39 is the probability that an NMAC encounter already occurring is with an aircraft without a Mode C transponder and represents the area in which the greatest improvement can be obtained. Of the remaining .034 (.424 - .39), .02 is due to surveillance failure. The balance, .014 (an order of magnitude lower than that due to transponder non-equipage), is composed of altimetry errors and the maneuvering intruder hazard.

# 8. SENSITIVITY ANALYSIS

The analysis of Section 7 used the best estimates based on available data for transponder equipage, surveillance failure, altimetry error, and the likelihood of a sudden intruder maneuver. It assumed that visual acquisition allowed the pilot to separate himself from the threat and that the RA was followed under all non-visual conditions. This section discusses the sensitivity of the results to each of those assumptions.

## 8.1 Error Rates and Assumptions Analyzed

Sensitivity of five basic system fault probabilities was tested in this analysis: Mode C equipage, surveillance failure, altimetry error, maneuvering intruder hazard, and human factors. To test the change in the probability of events 2-000 and 2-500 (and thus the top event) corresponding to changes in failure rates of these elements, the failure rates were varied between bounds judged appropriate for each element, as follows:

- Equipage: The nominal probability for an encounter with a Mode C aircraft is .61. To test the effect of this factor, the calculations were also run assuming all aircraft Mode C equipped.

- Surveillance: The nominal surveillance track probability is .94 for a TA and .97 for an RA. This quantity was explored by alternatively improving surveillance by a factor of three and degrading it by a factor of about two (e.g., probability of receiving RA varied from .99 to .94).

- Altimetry error. The only significant component is that ascribed to general aviation aircraft (uncorrected static error). The nominal errors (standard deviation) are given in Table 4-2. Sensitivity to this parameter was tested both by varying it plus and minus 20 percent; and by changing the form of the distribution from Gaussian to exponential.

- Maneuvering Intruder Hazard: The overall probability of encountering an intruder that would start maneuvering in such a manner and at just the time to "fake out" the TCAS and cause an NMAC was estimated from airborne data. The sensitivity to this factor was explored by changing the maneuver probability by 50 percent, both higher and lower.

- Human Factors. In the nominal case, no pilot failure modes were accounted for, although five were identified. To give some indication of the effect of these failure modes, they were permitted to fail at the rate of 1 in 20.

Also, three basic assumptions were made in the nominal estimate: TAs were not given on aircraft that are transponder equipped, but which do not report Mode C; visual acquisition, as enhanced by the TCAS, is used to provide separation, and RAs are followed in instrument meteorological conditions (IMC). The sensitivity analysis tests the opposing assumptions: that TAs are given on non-Mode C aircraft, that enhanced visual acquisition is completely ineffective (e.g. no TA display), and that RAs are not followed in IMC.

In the analysis that follows, each of these variations is assessed individually. The relevant probabilities are changed, and the analysis shown in Section 7 is repeated to obtain new probabilities for the top events. The resulting probabilities and their impacts on the calculations are described.

## 8.2 Changes in Individual Failure Probabilities

Table 8-1 describes the parameters which were varied individually in the fault tree to analyze these scenarios; it is a modification of Table 7-2, Column 2 lists the events that the parameter affects; the number or letter listed refers to the event listed in Table 7-2. Column 3 lists the value of this probability used in the nominal analysis of Section 7; column 4 lists the changed probabilities to be analyzed.

In the surveillance failure case, failure rates 1.b. and 4.b. from Table 7-2 change at the same time; in the altimetry error case, both 5.a. and 6.a. change; and in the case of visual acquisition not effective, failure rates for acquisition by the time of the RA and by 15 seconds prior to CPA both become unity.

Note in the case of altimetry, we did not vary the failure rate itself but instead the cause of the failure rate, altimetry error. A 20 percent larger altimetry error produced more than double the failure rate for inadequate RAs and RAs which induced an NMAC; a 20 percent lower altimetry error lowered the failure rate to less than half its nominal value. Using the nominal altimetry error and changing the distribution from Gaussian to exponential, as noted in Section 4.2.4.2, produced the changed input probabilities listed in Table 8-1.

TABLE 8-1
CHANGES IN FAULT TREE INPUT PROBABILITIES

| PARAMETER | EVENT (Table 7-2) | NOMINAL PROBABILITY (Section 7) | SENSITIVITY VALUES | |
|---|---|---|---|---|
| 1. Mode C equipage | 1.) No TA is displayed | .43 | .06 | |
| | 1.a.) Encounter with a non-Mode C-equipped aircraft | .41 | 0.0 | |
| | 4.) No RA is displayed | .42 | .03 | |
| | 4.a.) Encounter with a non-Mode C-equipped aircraft | .39 | 0.0 | |
| 2. Surveillance failures | 1.b.) Surveillance does not acquire threat in time for TA | .06 | .10 | .02 |
| | 4.b.) Surveillance does not acquire threat in time for RA | .03 | .06 | .01 |
| 3. Altimetry error magnitude | 5.a.) Inadequate RA is displayed | .011 | .027 | .0041 |
| | 6.a.) RA is displayed which will lead to NMAC* | .0081 | .022 | .0024 |
| 4. Altimetry error distribution | 5.a.) Inadequate RA is displayed | .011 | .023 | |
| | 6.a.) RA is displayed which will lead to NMAC* | .0081 | .018 | |
| 5. Maneuvering intruder hazard | 6.b.) RA is displayed which will lead to NMAC* | .016 | .024, | .008 |
| 6. Human factors failures | Inappropriate pilot reaction (per decision/encounter) | 0.0 | | .05 |
| 7. Non-Mode C tracking | 1.) No TA is displayed | .43 | .14 | |
| | 1.a) Encounter is with non-transponder aircraft | .39 | .08 | |
| 8. Visual Acquisition Ineffective | 3.) Pilot does not visually acquire aircraft (in good VMC with TA as aid) | | | |
| | 3.a.) In time to avoid NMAC (15 sec. prior to CPA) | .17 | 1.0 | |
| | 3.b.) Prior to RA | .35 | 1.0 | |
| 9. Do not follow RA in IMC | (No probability involved; 16 percent of RAs issued not used.) | | | |

* Assumes 61% of encounters with Mode C-equipped aircraft, 97% surveillance acqusition rate.

## 8.3 Changes in Overall Failure Probabilities

The resulting changes in probability for events 2-000, 2-500 and the top event are listed in Table 8-2. They are graphed in Figure 8-1 on a logarithmic scale to show the small changes in magnitude for event 2-500 more clearly. The lines across the bars represent the nominal probability of each event. It should be noted that a change in probability of event 2-000 is accompanied by a corresponding change in the probability of event 2-500 in most cases. For example, higher Mode C equipage results in a much lower probability of an unresolved NMAC but a higher probability of an induced NMAC.

Surveillance failure has little effect on the probability of both unresolved and induced NMACs. Altimetry error and maneuvering intruder hazards have no discernable impact on unresolved NMACs, but induced NMACs are sensitive to these factors. If, instead of the Gaussian error model, an exponential error model is assumed and the failure probabilities are calculated, the effect is similar to using the Gaussian model with about a 15 percent increase in nominal error.

If TAs were to be provided on non-Mode C aircraft, there would be a significant reduction in the unresolved NMACs without an increase in induced NMACs.

Improved visual acquisition, arising from the presentation of TAs, has little effect on unresolved NMACs. This is due to the fact that since only Mode C aircraft are tracked, there is high probability of getting an RA, given the TA; the effect of visual acquisition is to correct inadequate RAs, which are infrequent. For induced NMACs, the benefit of improved visual acquisition

TABLE 8-2
CHANGES IN FAULT TREE TOP EVENT PROBABILITIES

| | PROBABILITY OF | | |
|---|---|---|---|
| | TOP EVENT (NMAC) | EVENT 000 (UNRESOLVED NMAC) | EVENT 500 INDUCED NMAC |
| Nominal Case | .424 | .413 | .011 |
| If 100% Mode C | .053 | .035 | .018 |
| If surveillance failure is 1/3 | .410 | .399 | .011 |
| 2x | .441 | .430 | .011 |
| If GA altimetry if 20% improved | .419 | .411 | .008 |
| worse | .434 | .417 | .017 |
| If GA altimetry error distribution exponential | .431 | .416 | .015 |
| If the maneuvering intruder hazard is 50% less likely | .421 | .413 | .008 |
| more likely | .428 | .413 | .014 |
| If human factors failures are .05 | .484 | .442 | .042 |
| If TAs are given for non-Mode C | .249 | .238 | .011 |
| If visual acquisition ineffective | .441 | .416 | .025 |
| If RAs not followed in IMC | .514 | .507 | .007 |

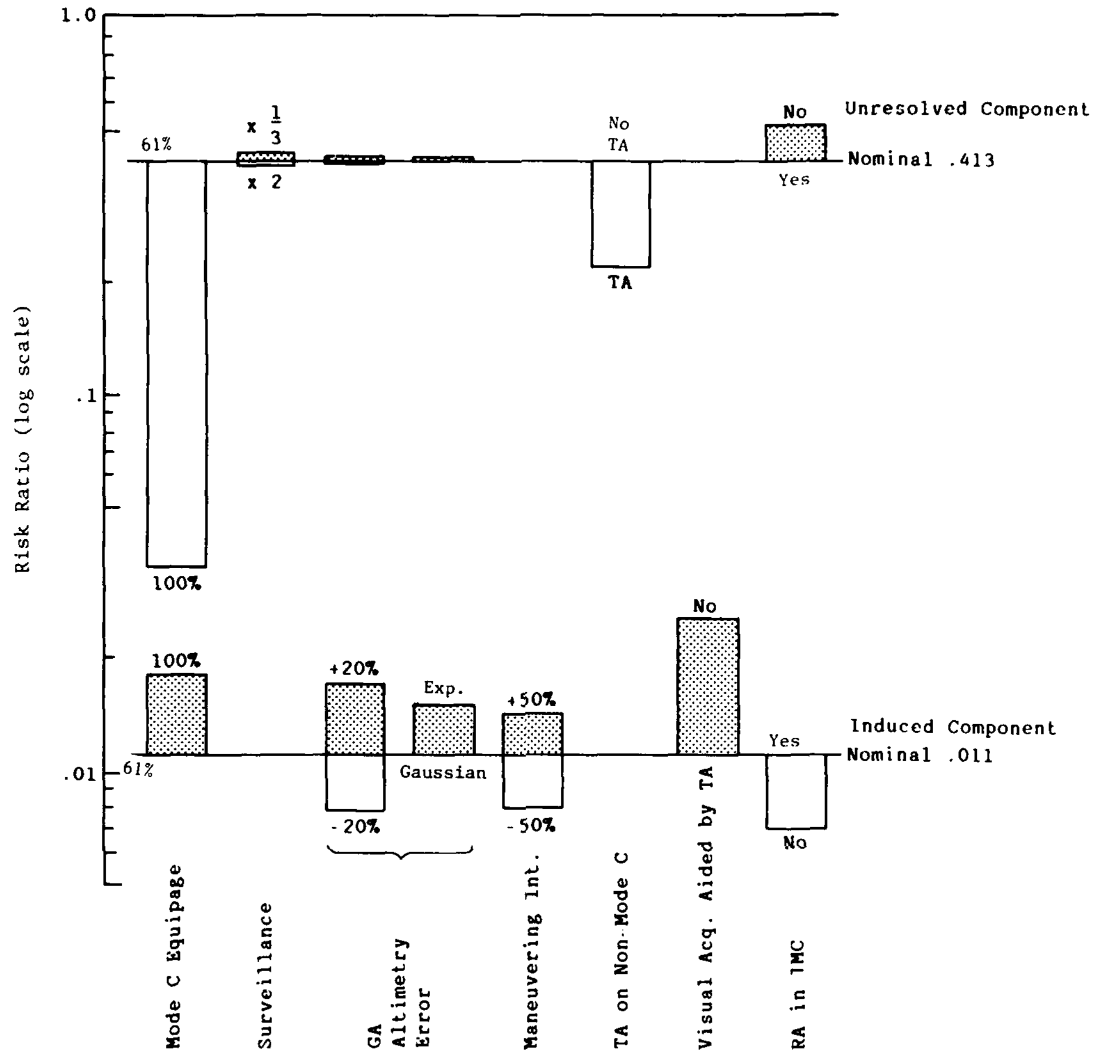



**FIGURE 8-1**
**INFLUENCE OF VARIOUS FACTORS ON OVERALL SYSTEM PERFORMANCE**

can be seen by observing that without any TAs (visual acquisition ineffective) that portion of the failure rate approximately doubles.

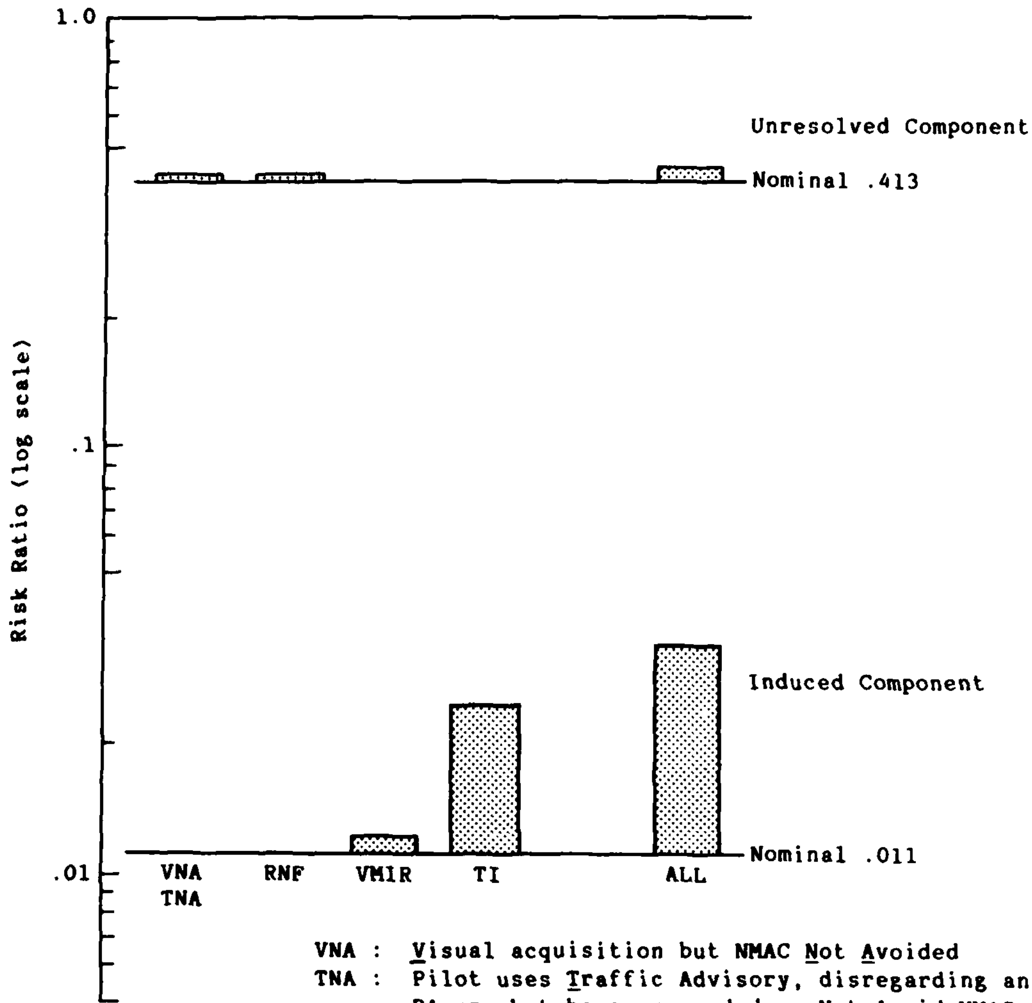
By not following RAs in IMC, we can avert a substantial number of induced NMACs as shown by the bar on the right side of Figure 8-1; however, this also increases the number of unresolved NMACs.

### 8.4 Human Factors

To obtain some indication of the effect of human factors failure modes, a conservative failure rate of .05 (1 failure every 20 situations in which the potential for failure exists) was used. The individual failures have been broken down into their five components (VNA, TNA, RNF, VMIR, and TI) and graphed in Figure 8-2, using the same scale as Figure 8-1.

It can be seen from the graph that human factors has little impact on the unresolved component of the failure rate, which is only slightly sensitive to VNA (intruder was visually acquired but NMAC not avoided), TNA (TA misleads the pilot into disregarding visual acquisition or a correct RA), and RNF (RA not followed). The unresolved component is very insensitive to VMIR (Maneuver on an incorrect RA in spite of visual acquisition indications) because the opportunity to make this error is infrequent (.08% of all NMAC encounters). TI (use of the Traffic Advisory, inducing an NMAC ) does not apply to the unresolved component.

As for the induced component, it can be seen that the potential exists for a significant number of failures by use of the Traffic Advisory to make an incorrect maneuver which induces an NMAC. It should be noted, however, that this may be an over-estimate for the following reasons:




VNA : Visual acquisition but NMAC Not Avoided
TNA : Pilot uses Traffic Advisory, disregarding an RA or what he sees, and does Not Avoid NMAC
RNF : Resolution Advisory Not Followed
VMIR: Visual acquisition, but pilot still Maneuvers on an Incorrect RA
TI : Pilot maneuvers based on TA, Inducing an NMAC

Note: Assumed failure rate for each factor is .05; for all factors at once they are also .05.

**FIGURE 8-2**
**INFLUENCE OF HUMAN FACTORS ON OVERALL SYSTEM PERFORMANCE**

1. Pilot training should reduce the use of the TA for purposes other than as an aid to visual acquisition.

2. If the TA is used for maneuvering, we assumed the following conservative conditions:

   a. Visual acquisition is not attempted or is not possible

   b. If the display is accurate, the pilot must interpret it adversely, and disregard any ensuing RA (actually, a chain of concurrent probabilities).

As can be seen in Figure 8-2, the induced component of the failure rate is not sensitive to the other factors (VMIR, RNF, TNA, or VNA).

If all five factors were to fail independently at the rate of 1 in 20, the relative probability of an NMAC would be 48.4 percent, with the unresolved component being 44.2 percent and the induced component being 4.2 percent as was listed in Table 8-2.

## 9. FINDINGS

Reviewing the approach used in this study, a term called Risk Ratio was defined and computed using real-world data. This factor is the risk of encountering a critical near midair collision (NMAC) when equipped with TCAS, relative to the risk when not so equipped. Using the NMAC as a defined failure condition provides a quantitative measure for calculations; using the Risk Ratio places the calculations of System Safety on a direct comparative basis.

The basic philosphy is to make the assessment realistic, but conservative. In particular, no credit was assumed for the following:

- Visual acquisition in less than bright daylight conditions
- The "Advisory Not OK" feature
- Aircraft leveling out gradually instead of abruptly
- The Resolution Advisory preventing an incorrect maneuver, or correcting one that may have been prematurely taken on a Traffic Advisory

The data and analyses brought to focus in this study disclose the following findings relative to the Risk Ratio.

1. Under a nominal set of baseline conditions this ratio is about 42 percent. Figure 9-1 shows this, with the first bar (100 percent) as the pre-existing risk of encountering an NMAC without TCAS; the second bar (Risk Ratio is 42 percent) is the risk of encountering an NMAC with TCAS under the nominal conditions. Most of this residue is attributable to the lack of complete equipage with altitude reporting transponders.

   If the capability to track all non-Mode C aircraft and display an "altitude unknown" Traffic Advisory were added to the nominal system, a major reduction in the unresolved component of the Risk Ratio would be obtained; the residue would decrease to about 25 percent, as shown in the third bar of Figure 9-1. This is caused by the improved visual acquisition that would result for those aircraft that are on a near collision course.

   The greatest payoff, however, in reducing the risk of NMACs would be to increase the fraction of aircraft having altitude reporting transponders. Statistics on avionics show the trend to be in that direction. If all aircraft were equipped with altituding reporting transponders, the Risk Ratio would decrease to 5 percent (the fourth bar of Figure 9-1), two thirds of which is attributable to surveillance limitations; the remainder is attributable to maneuvering intruders and to altimetry error.

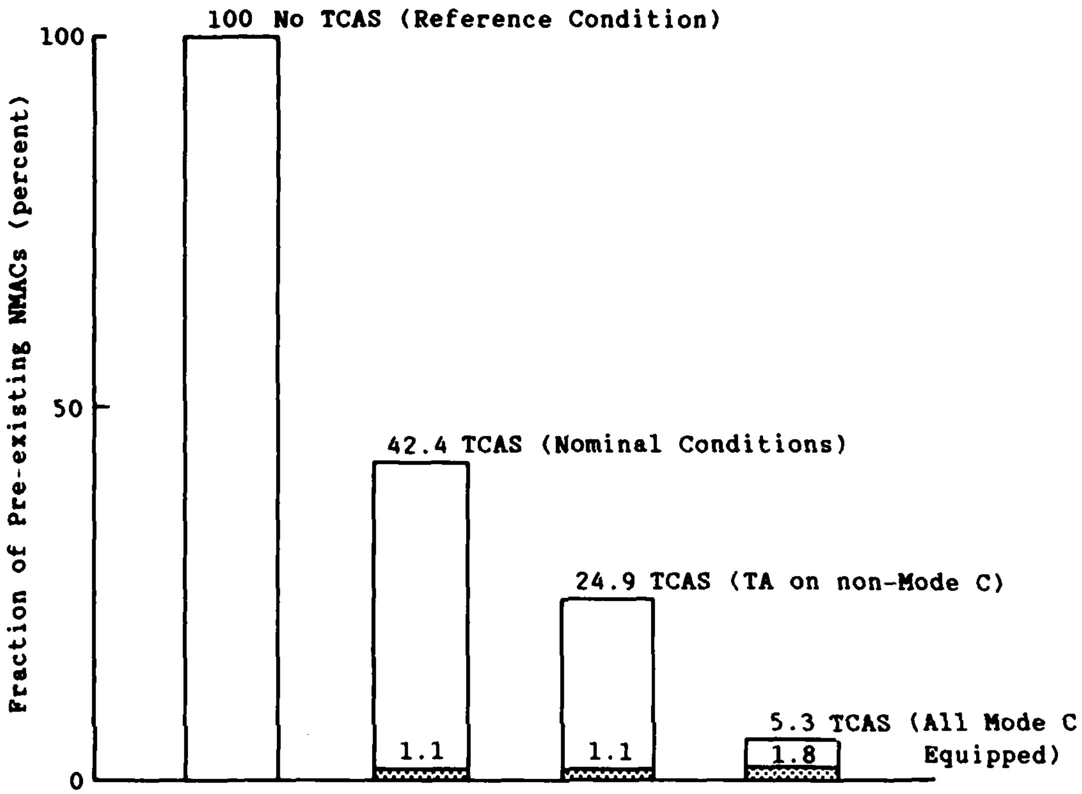



**FIGURE 9-1**
**RELATIVE TCAS EFFECTS**

2. Most of the residue under nominal conditions is caused by an inability to avoid an NMAC that would have occurred even without TCAS (the unresolved component of Risk Ratio). Under certain conditions, however, the system itself can induce an NMAC (the induced component of Risk Ratio). The risk of that occurring for the nominal conditions is about one percent of the risk of encountering an NMAC without TCAS (shaded parts of the bars in Figure 9-1; see also Table 9-1). The primary cause for these failures are altimetry errors and sudden maneuvers by the intruder.

   If the standard deviation (Gaussian distribution) of general aviation altimetry error were to be 20 percent larger than estimated, the induced component of Risk Ratio would increase to about 1.7 percent. While this component is small relative to the unresolved component, and the overall effect on Risk Ratio is small, the minimization of induced NMACs is in itself a major TCAS objective. If the assumed error distribution were characterized by the heavy tailed symmetrical-exponential distribution instead of the Gaussian, the nominal induced component of Risk Ratio would be 1.5 percent -- somewhat larger than before but similar in effect.

   The contribution of altimetry error to the total overall Risk Ratio is dominated by the GA errors; the hazard caused by air carrier errors is at least an order of magnitude lower. A reduction of the GA altimetry error provides more than proportionate reduction in the induced component of the Risk Ratio.

TABLE 9-1
SENSITIVITY TO VARIOUS FACTORS

| CONDITION | OVERALL RISK RATIO (Percent) | UNRESOLVED COMPONENT (Percent) | INDUCED COMPONENT (Percent) |
|---|---|---|---|
| Nominal | 42.4 | 41.3 | 1.1 |
| Non-Mode C Traffic Advisories | 24.9 | 23.8 | 1.1 |
| 100% Mode C Equipage | 5.3 | 3.5 | 1.8 |
| 20% Higher GA Altimetry Error | 43.4 | 41.7 | 1.7 |
| Exponential Altimetry Error Model | 43.1 | 41.6 | 1.5 |
| 50% Increase in Probability of Fake-out Maneuver | 42.8 | 41.3 | 1.4 |
| Probability of Missed Surveillance. 30% of Nominal | 41.0 | 39.9 | 1.1 |
| Aided Visual Acquisition Not Effective | 44.1 | 41.6 | 2.5 |
| TCAS Not Used in IMC | 51.4 | 50.7 | .7 |
| Human Factor Failures: One Per 20 Encounters | 48.4 | 44.2 | 4.2 |

The risk of two air carriers, both equipped with TCAS, having an NMAC is several orders of magnitude less than without TCAS; altimetry is corrected, maneuvers are coordinated, and both aircraft have surveillance.

3. TCAS is susceptible to being thwarted, in certain cases, by an intruder making a sudden vertical maneuver. The situation of most concern is one in which an intruder with a substantial vertical rate approaches a level TCAS aircraft so as to project a crossing through its altitude. A vertical escape initiated by the TCAS aircraft could be thwarted ("faked out") if the intruder were suddenly to level off at a critical time and altitude. The study used actual aircraft data from Piedmont flights and from FAA flights to estimate the contribution of this factor to overall Risk Ratio. A 50 percent increase in the probability of a fakeout maneuver will cause a nearly proportionate increase in the induced component (increases the induced component of Risk Ratio from 1.1 percent to 1.4 percent).

4. The nominal performance of surveillance quality was estimated from live track data in many regions of airspace. If the missed track rate were to decrease from its nominal rate of three percent to one percent, a small improvement in the unresolved component of Risk Ratio would be obtained; the induced component is essentially unaffected.

5. A Traffic Advisory is displayed on an intruder approximately 15 seconds before the Resolution Advisory is posted. This precursor is intended to alert the pilot to start a visual search for an aircraft that may be of concern. If visual acquisition is obtained, an incorrect Resolution Advisory, such as from altimetry error, can be overriden by the pilot. This aided acquisition reduces the induced component of Risk Ratio by more than half. Very little effect occurs for the unresolved component, as a Resolution Advisory almost always occurs if a Traffic Advisory is present.

6. If TCAS is not used in IMC, which constitutes roughly 16 percent of the NMACs, the unresolved component would correspondingly increase, and the induced component would correspondingly decrease.

7. The probability of encountering an NMAC in today's environment, in the absence of TCAS, is approximately once in 100,000 hours of flight. Four quite different approaches to obtaining this estimate were used, and they were all within 4:1 of this value.

8. Five pilot failure modes (human factors) were postulated and their relative impact parametrically assessed. The most severe failure postulated (TI) is one in which the pilot used the Traffic Advisory for maneuvering rather than for visual acquisition, made an inappropriate maneuver, and disregarded any

subsequent Resolution Advisory. The second most severe human factor failure is one in which the Resolution Advisory is simply not followed.

If all five human factor failures were to fail independently at the rate of 1 in 20, the Risk Ratio would be about 48 percent, with the induced component accounting for 4.2 percent.

## 10. CONCLUSIONS AND RECOMMENDATIONS

### Operational Implications

Operational discipline for the use of TCAS will vary depending on many factors. However, it was found that: 1) visual acquisition, as aided by the Traffic Advisory display, can play an important role both in improving see-and-avoid and in minimizing the effects that would induce critical NMACs, (2) alertness remains necessary in visual conditions both to protect against aircraft not equipped with transponders and, to a much lesser extent, to protect against equipped aircraft which may be missed by TCAS surveillance.

If TCAS is not used in IMC, the induced component of NMACs would decrease; however, the larger benefit of being able to resolve NMACs in IMC would also decrease.

### Training Implications

During the course of this System Safety study, several factors that should be addressed in a training and proficiency program became apparent.

1. Traffic Advisories are intended to aid visual acquisition and to prepare the pilot should a Resolution Advisory follow. Premature maneuvering based on the Traffic Advisory alone could be self defeating.

2. Prompt reaction when a Resolution Advisory is posted is important. In order to be able to

maneuver through the uncertainties of altimetry error, a displacement on the order of 400-500 ft may be necessary (larger at high altitudes). A delayed reaction will reduce the displacement achievable in the available time.

3. From the results of the study it appears that the pilot is statistically better off by trusting his instrument than by not trusting it -- the ratio of resolving NMACs to inducing them is 23:1. If, in addition, Traffic Advisories are used to aid visual acquisition, this ratio increases to 58:1.

Equipment Reliability Implications

The type of equipment failure of concern for this study is one which could cause an NMAC. If one occurs which does not cause the performance monitor to immediately turn off TCAS, it should be at the rate of $10^{-4}$, or less, per NMAC to be negligible relative to other causes. The performance monitor therefore needs to be effective in detecting critical sources of failure in the elements of the TCAS system.

Program Implications

The System Safety study highlighted several recommended areas that the TCAS Program might emphasize in the future.

1. Steps should be initiated to confirm applications of TCAS in IMC. A determination of the detailed nature of altimetry and of maneuvering intruders

under poor visibility conditions should be obtained and methods explored for controlling them.

2. Identify steps that might be undertaken to remove out-of-tolerance altimeters from the system.

3. Develop pilot training measures to specifically treat human-factor failure modes that have been identified. Consider means to verify the effectiveness of such steps.

Changes Required

This study resulted in an intensive evaluation of all safety-related parameters and procedures. It was concluded that an increase of the ALIM parameter at low altitudes appears desirable. This would decrease the effects of altimetry error and would not affect the alarm rate significantly.

## APPENDIX A

## LIST OF GOVERNMENT/INDUSTRY REVIEWERS

The following list of individuals participated in several status reviews held during the course of the System Safety study.

Mr. Barry Billmann
Federal Aviation Administration Technical Center

Mr. Thomas A. Choyce
Federal Aviation Administration Technical Center

Mr. Adfred L. Adkins
Federal Aviation Administration Technical Center

Ms. Wendie F. Chapman
Federal Aviation Administration

Mr. Harold W. Becker
Federal Aviation Administration

Lt. Col. James Williams (DOD liaison)
Federal Aviation Administration

Mr. William L. Hyland
Federal Aviation Administration

Mr. James Treacy
Federal Aviation Administration

Mr. Raymond Stoer
Federal Aviation Administration

Mr. Robert Miller
Federal Aviation Administration

Mr. Quentin Smith
Federal Aviation Administration

Mr. Ken Peppard
Federal Aviation Administration

Mr. David West
Federal Aviation Administration

Col. Wilfred G. Volkstadt
United States Air Force/Federal Aviation Administration

Mr. Richard Bowers
Air Transport Association of America

Mr. Ward Baker
Air Line Pilots Association International

Mr. Dennis Wright
Aircraft Owners & Pilots Association

Mr. J.C. Snodgrass
Aerospace Industries Association of America

Mr. Robert Buley
Republic Airlines

Mr. Frank C. White
Dalmo Victor Operations

Mr. Gilbert F. Quinby
Consultant

Captain David Simmon
United Airlines

Mr. George Litchford
Litchstreet

Mr. George K. Schwind
United Airlines

Mr. Burton Hulland
Hulland Engineering

Mr. Harold H. Fink
Aeronautical Radio, Incorporated

Mr. E.W. Fretwell
Air Line Pilots Association International

Mr. Arthur D. McComas
Bendix

Mr. Ulf Gustafsson
United Airlines

Captain Ray Jones
Delta Airlines

Mr. Robert D. Force
Boeing Commercial Airplane Company

Mr. J.M. Graham
Douglas Aircraft

Dr. E.W. Holcomb
Boeing Commercial Airplane Company

## APPENDIX B

## AN ESTIMATION OF THE PROBABILITY OF HORIZONTAL MISS DISTANCE, GIVEN A TCAS ALARM

It is of interest to estimate the probability that two aircraft will approach within a given horizontal distance after a TCAS advisory (RA or TA) is posted. The following analysis employs the modified Tau criterion for alarm and develops a simple estimate of that probability based on non-accelerating flight; it is abstracted from several notes written by Joseph J. Fee.

The encounter geometry is illustrated in Figure B-1. The circle with radius S represents the desired separation in the horizontal plane at the closest point of approach. The intruder approaches with relative velocity V, having a radial component $V_r$ and a tangential component $V_t$.

The necessary condition for an alarm to be generated is that the modified TAU criterion must be met. That is,

$$TAU = -\frac{(R-R_o)}{V_r}$$

or

$$V_r = -\frac{(R-R_o)}{TAU} \qquad \text{(B-1)}$$

where $R_o$ = minimum range parameter

$R$ = range to threat

$V_r$ = radial velocity

TAU = approximate time to closest approach

The sufficient condition for alarm initiation follows from the

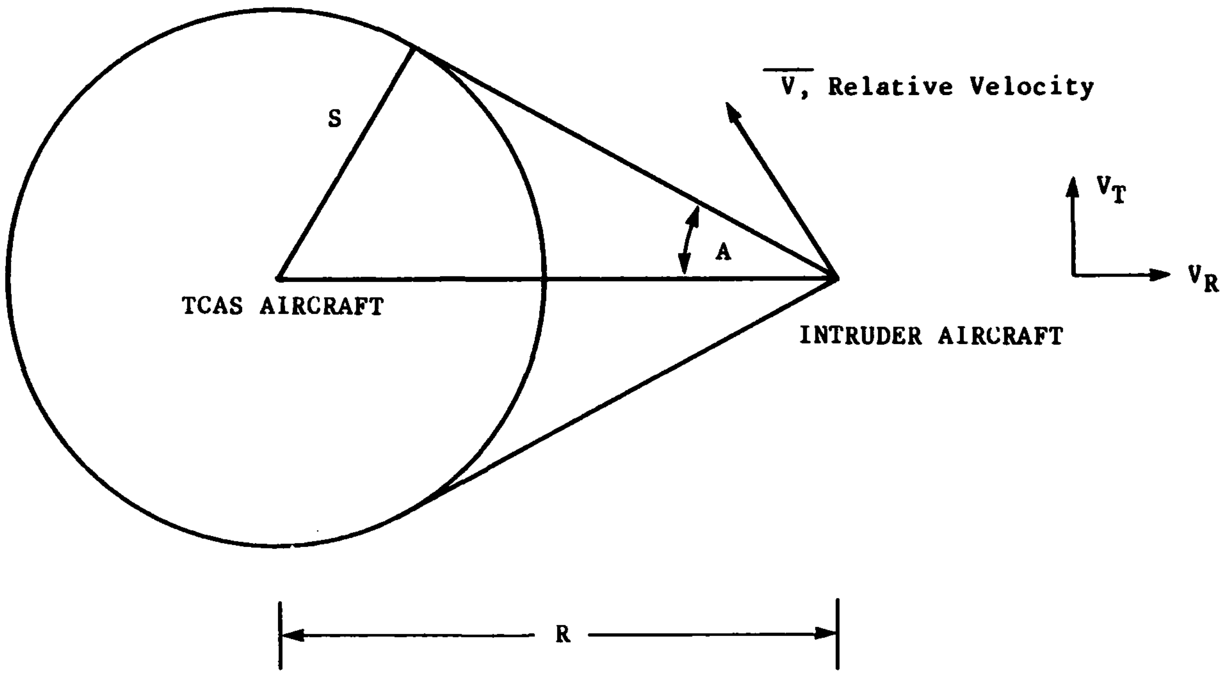



**FIGURE B-1**
**TCAS MISS DISTANCE GEOMETRY**

requirement that the radial velocity, $V_r$, be both negative and decreasing more rapidly than the alarm threshold:

$$\frac{dV_r}{dt} = \frac{d}{dt}\frac{(R_o - R)}{TAU}$$

$$\dot{V}_r = W^2 R = \frac{-V_r}{TAU} \qquad \text{(since } \dot{R} = V_r \text{ at alarm threshold)}$$

where $W = V_t/R$

After some manipulation, this gives a constraint on the magnitude of the relative tangential velocity:

$$|V_t| \leq |V_r| \quad \left(\frac{R}{R-R_o}\right)^{1/2} \quad (R > R_o) \qquad \text{(B-2)}$$

in addition to the constraint previously imposed on the radial velocity.

For a specified minimum separation, the constraint on $V_t$ is given by the geometry requirement:

$$\frac{V_t}{V_r} \leq \tan A$$

or:

$$|V_t| \leq |V_r| \quad \frac{S}{(R^2 - S^2)^{1/2}} \qquad \text{(B-3)}$$

These equations can be utilized in computing the probability of alarm and likelihood of approaching within separation S, by assuming a random distribution for the encounter relative velocity. In the following development, two assumptions are made with respect to the randomness of encounter:

a. The TCAS is operating in steady state fashion, i.e., the encounters typically occur singly and at the minimum radial relative velocity corresponding to the range at alarm initiation.

b. The relative velocity is uniformly distributed in bearing over $2\pi$ radians and in magnitude between 0 and $V_{max}$ (from Piedmont data).

The computation of probability is illustrated in Figure B-2:

1. For each range, the range rate is computed for TAU alarm.

2. The probability of TAU alarm and S separation as a function of each range is computed over an incremental range rate ($\Delta V_r$). This is shown in terms of the incremental sector areas in Figure B-2, where the circle represents the uniform probability distribution of velocity which is the same for all ranges

3. The overall probability of alarm and near miss is computed by integrating over all ranges between $R_o$ and $R_m$ (the mean range at which alarm occurs -- from Piedmont data).

4. The probability of an intruder coming within 500 feet (laterally) of TCAS, given a TAU alarm is simply:

$$P_{S|A} = \frac{\text{Probability of Near Miss}}{\text{Probability of TAU Alarm}}$$

Referring to Figure B-2, the ratio of incremental probabilities

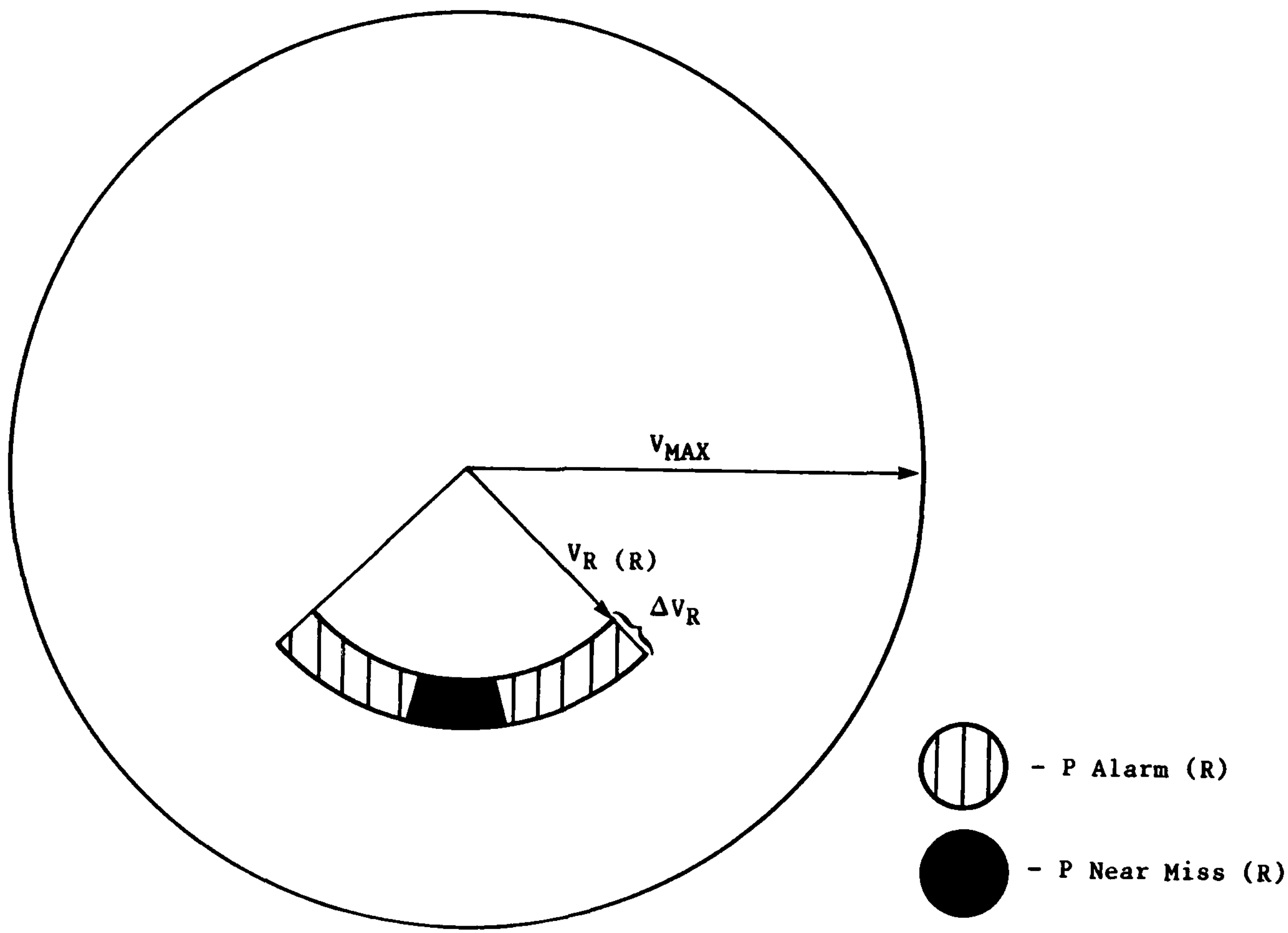



**FIGURE B-2**
**ILLUSTRATION OF PROBABILITY COMPUTATION**

shown is directly proportional to the ratio of angular arcs corresponding to probability of near miss and TAU alarm, respectively. For a given radius R, greater than $R_o$, equation B-2 implies that $V_t$ is approximately equal to $V_r$, from which it follows that TAU alarms will be given for relative velocities within approximately $\pm$ 45 degrees of a head-on encounter. Similarly, for R greater than $R_o$, equation B-3 implies that the angular sector in which a near miss can occur is approximately proportional to:

$$\frac{V_t}{V_r} \doteq \frac{S}{R}$$

and decreases as R increases.

Using $R_o$ = .3 nmi, TAU = 25s, and observing from the Piedmont data base that the maximum relative velocity was 857 knots, one can calculate the probability of a near miss (less than 500 ft), given an alarm, by using the procedure depicted in Figure B-2. The result is:

$$P_{S|A} = .028$$

# APPENDIX C

## PROBABILITY OF POTENTIAL FAKE-OUT MANEUVER FROM FAA FLIGHT DATA

In Section 3.3 the airspace was characterized from data taken by FAA flights of TCAS equipment. This Appendix utilizes that data to estimate the probability of a fake-out maneuver.

The factors to consider in determining the probability of a potential fake-out maneuver are vertical separation at CPA, horizontal separation at CPA, vertical rate of intruder and probability of a profile change. Table C-1 presents the probabilities of these factors, as determined from Section 3.3.

TABLE C-1
PROBABILITY OF FAKE-OUT MANEUVER
GIVEN A PROXIMATE ENCOUNTER

| FACTOR | PROBABILITY |
|---|---|
| VERTICAL RATE GREATER THAN 1200 FPM | .12 |
| VERTICAL SEPARATION AT CPA BETWEEN 500' and 800' | .076 |
| HORIZONTAL SEPARATION AT CPA LESS THAN .1 NAUTICAL MILES | .0005 |
| PROFILE CHANGE IN 40 SECOND PERIOD | .125 |
| | $5.70 \times 10^{-7}$ Probability of Fake-out Maneuver |

This is compared with other results in Section 4.2.6.

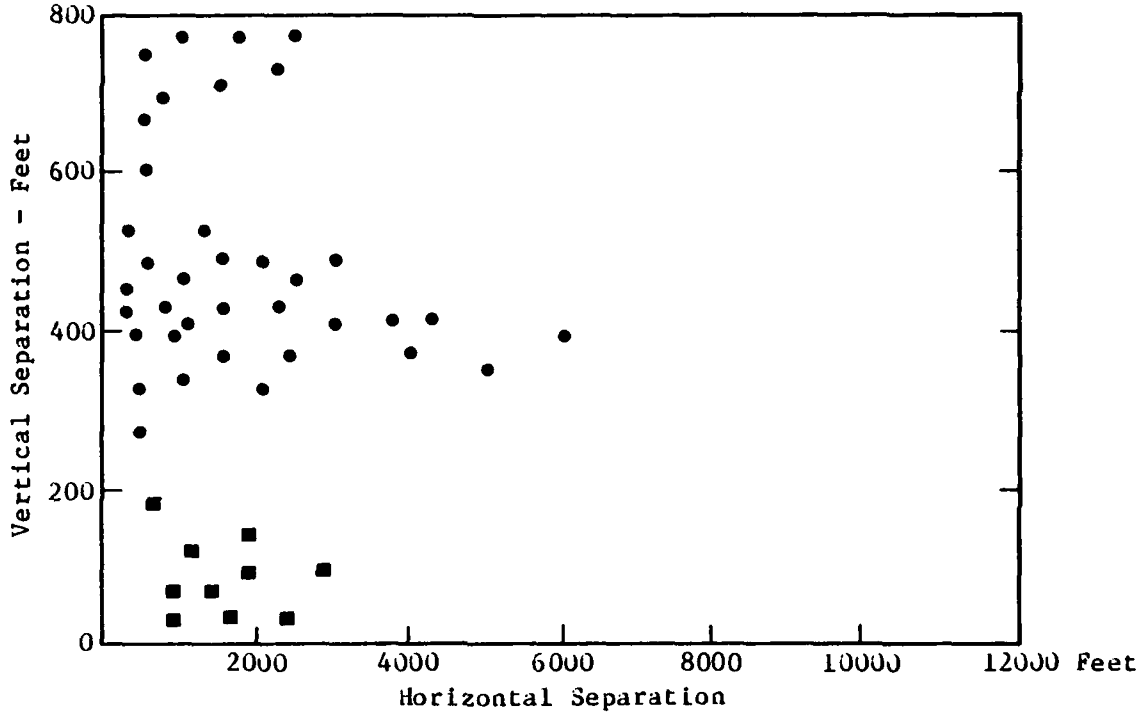
# APPENDIX D

## TCAS RESOLUTION PERFORMANCE

During early testing of TCAS at the FAA Technical Center, procedures included responding to TCAS alarms on most flights. The pilots were directed to respond with a smooth acceleration to a 1000 feet per minute escape rate, if they were level. If the aircraft was already in a steady state vertical maneuver, they were to attempt to increase the vertical rate by 500 feet per minute, if the RA was in the direction of the current maneuver. Post flight analysis indicated the escape accelerations averaged 1/8 g. The achieved escape rates from level flight conditions slightly exceeded the goal rate of 1000 feet per minute. (Note: It is now envisioned that the pilot will escape at 1500 fpm, or at current rate if that exceeds 1500 fpm.)

During testing with preplanned encounters the Tau value used for alarming was 25 seconds. The vertical threshold for negative Resolutions Advisories was 750 feet for all encounters. The predicted vertical separation parameter for positive Resolution Advisories, ALIM, was either 340 or 440 feet depending on whether the TCAS aircraft was above or below 10,000 feet MSL.

Figure D-1 depicts the CPA conditions which resulted following TCAS alarms requiring a pilot response. Included are all level flight encounters which resulted in positive resolution advisories and encounters with negative advisories which caused the pilot to change his rate or direction of vertical movement. The squares denote cases which called for pilot




Technical Center Flights

● = Pilot Responded

■ = Pilot Did Not Respond

**FIGURE D-1**
**CPA CONDITIONS FOLLOWING**
**CORRECTIVE RESOLUTION ADVISORIES**

response but no response was made due to the testing procedures being used on that particular flight.

Figure D-1 indicates a high proportion of the vertical separations concentrated between 350 and 600 feet. This reflects the achievement of sufficient vertical separation since ALIM was either 340 or 440 feet and the TCAS aircraft could then return to level flight. Several encounters which resulted in Resolution Advisories were planned to have more than 2 nautical miles horizontal separation at CPA. The horizontal distance in these cases is off scale and the points are not included in Figure D-1.

Figure D-2 presents the cumulative distributions of vertical separation following TCAS corrective resolutions when both aircraft were in level flight. For the cases shown in Figure D-2, 65 percent of the encounters had initial vertical separations of 300 feet and the remaining 35 percent had initial vertical separations of 100 feet. Slightly larger vertical separation resulted for cases when ALIM was 440 feet. Ninety-five percent of the encounters resulted in vertical separation exceeding 350 feet. Vertical separation exceeded 400 feet 90 percent of the time.

Encounters in which the TCAS was in a steady state climb or descent, and the intruder was level, were also tested. Additionally, the roles of TCAS and the intruder were reversed. The steady state vertical rates tested were climbs and descents with rates of either 500, 1000 or 2000 feet per minute. For these scenarios the planned vertical separation at closest point of approach was 0 feet. The separation results are presented in Figure D-3.

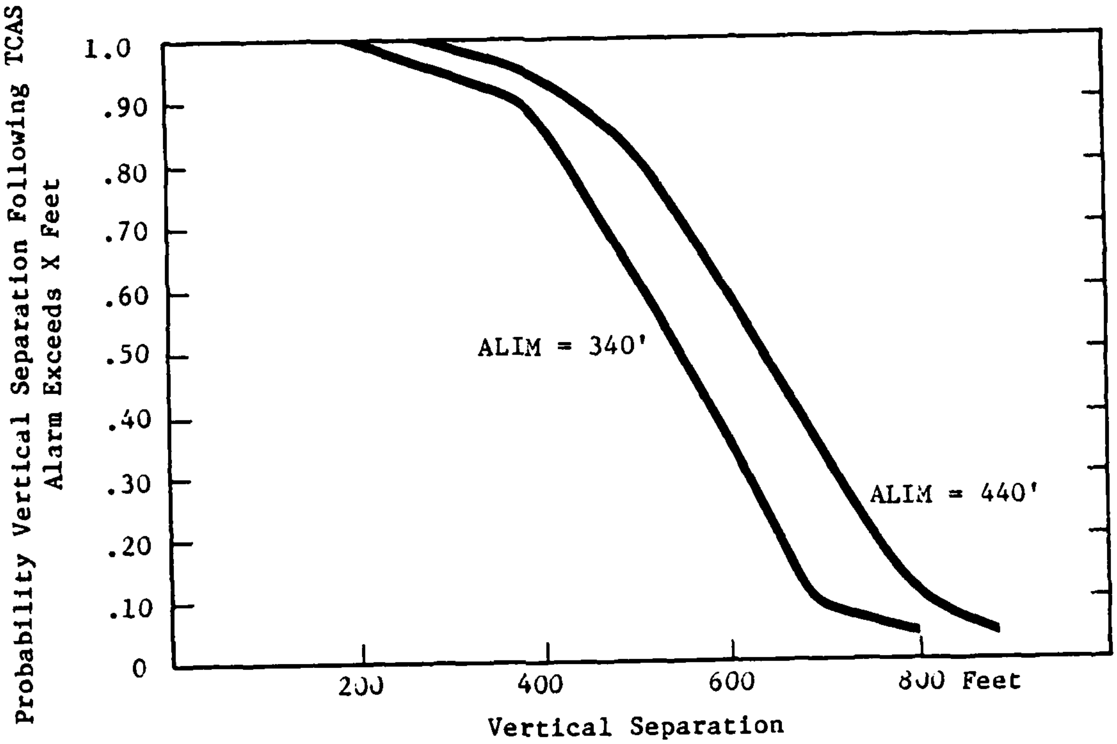



**FIGURE D-2**
**TCAS RESOLUTION PERFORMANCE**
**(BOTH AIRCRAFT LEVEL)**

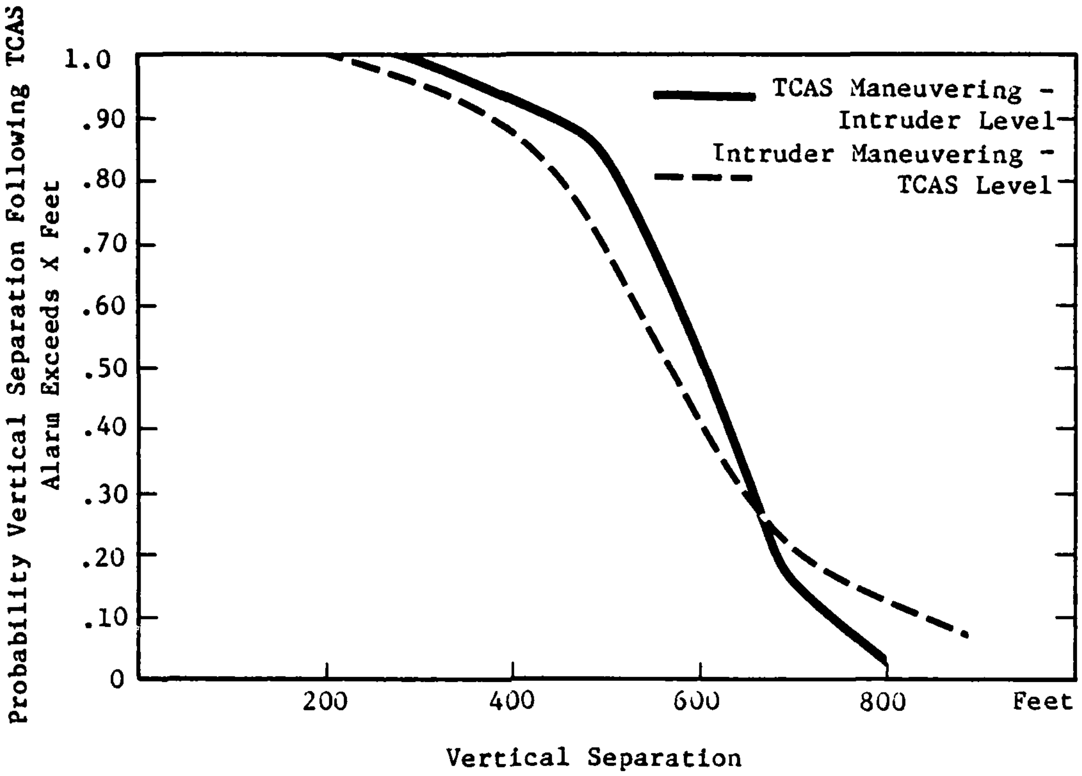



**FIGURE D-3**
**TCAS RESOLUTION PERFORMANCE**
**(ONE AIRCRAFT WITH VERTICAL RATE)**

In 97 percent of the encounters the resulting vertical separation exceeded 300 feet. In almost 90 percent of the encounters vertical separation exceeded 500 feet at CPA. The average separation and the 90th and 95th percentile separations were slightly larger for cases where TCAS was established in a climb or descent and the intruder was level at the time of the alarm.

# APPENDIX E

## SCOPE OF LOGIC TESTING AT THE FAA TECHNICAL CENTER

The FAA Technical Center has performed very thorough testing of the TCAS Collision Avoidance Logic. The logic testing activities have included both simulation testing of the collision avoidance software and live flight testing of the collision avoidance logic as implemented in the TCAS hardware. Logic testing has been an evolutionary process. In later stages of logic development, changes were tested by replaying the TCAS surveillance data which had been collected on previous TCAS test flights.

Initial testing involved the tailoring of the threat volumes to terminal operation characteristics. The Air Traffic Control Simulation Facility at the FAA Technical Center was configured to represent two different terminal areas, Chicago (O'Hare), and Knoxville, Tennessee. These simulations were used to develop the first estimates of the collision avoidance alarm rate. The result of this testing was reported in References 11, 12, and 13.

The performance of the collision avoidance logic to satisfactorily generate separation between conflicting aircraft was evaluated using the Fast Time Encounter Generator developed at the FAA Technical Center. This simulation tool permitted rapid analyses of TCAS performance for a large number of preplanned encounter scenarios. The scenarios included Mode C-only threats, TCAS equipped threats, and multiple intruders of various equipment configurations. Using the Fast Time Encounter Generator logic, sensitivity to several parametric encounter conditions was tested. The range of the parameter conditions are listed in Table E-1.

TABLE E-1
RANGE OF PARAMETRIC CONDITIONS EVALUATED

| ENCOUNTER CONDITION | SAMPLE PARAMETRIC RANGE |
|---|---|
| OWN VELOCITY | 150 to 550 knots in 100 kn increments |
| INTRUDER VELOCITY | 100 to 440 knots in 50 kn increments |
| OWN VERTICAL RATE | $\pm$3000, $\pm$1500, $\pm$1000, $\pm$500 fpm and level |
| INTRUDER VERTICAL RATE | Same as OWN Vertical Rate |
| VERTICAL SEPARATION AT CPA | OWN 1000' above to 1000' below intruder at CPA in increments of 100' |
| HORIZONTAL SEPARATION AT CPA | 0 to 3 nmi in 0.25 nmi increments |
| INTRUDER VERTICAL ACCELERATION | 0.1, 0.25 and 0.5 g |
| TIME OF ACCELERATION | 55 to 10 s prior to CPA in 5 s increments |
| INTRUDER HORIZONTAL MANEUVERS | Half standard rate, standard rate and twice standard rate turns |

The Fast Time Encounter Generator has been used to verify logic performance in over 70,000 separate encounter scenarios. The results of this testing is described in References 35, 36, 37, and 38.

Other testing has identified the impact of error degraded range and altitude data on TCAS performance. The ability of the TCAS logic to perform during periods of high track coast rates (40% to 45%) has been verified. The performance the TCAS logic in time correlated error degraded environment is discussed in Reference 39.

The results of the TCAS logic performance during 10 separate test flights has been thoroughly reviewed. The test flights were conducted in Washington, D.C., Atlantic City, and Chicago. The flights included both planned encounters and targets of opportunity. Other test activities have involved in-depth testing of specific portions of the TCAS logic. Particular emphasis has been placed on vertical tracking procedures. Results of this analysis are presented in References 40 and 41.

## APPENDIX F

## FAILURE MODE AND EFFECTS ANALYSIS

This section tabulates failure effects of portions of the TCAS system. The perspective is "bottom-up," or inverse to the fault tree, in that each failure is studied to deduce the worst possible effect it could cause. In some instances, more than one effect is listed, but would not occur simultaneously. The effects are stated in the form "missed RA," "incorrect RA," etc. An examination of the fault tree shows that these effects can combine with the geometry of an encounter and other factors, and may lead to the NMAC. Of course, effect (e.g., "Incorrect RA") does not necessarily lead to NMAC.

The TCAS equipment contains a Performance Monitor that turns the TCAS system off if a failure is detected. This section shows the effects of undetected failures. The level of hardware failures described is the functional level.

### FAILURE OF SYSTEM FUNCTIONS

| FAILURE | WORST POSSIBLE EFFECT(S) |
|---|---|
| TCAS Receiver Totally Fails | No aircraft tracked. All TA, RA missed. |
| Receiver Sensitivity Degrades | Late or intermittent tracks. Late TA, RA. |
| TCAS Interrogator Totally Fails | No aircraft tracked. All TA, RA missed. |

| | |
|---|---|
| Partial Failure of Whisper-Shout Hardware | Some tracks missed. No TA, RA. Some tracks garbled. Late TA, RA. |
| Interrogator Power Degraded | Late or intermittent tracks. Late TA, RA. |
| Processor or Memory | Missed RA. Incorrect RA. |
| RA Display | Missed RA. Incorrect RA. |
| TA Display | Missed TA. Incorrect TA. |
| Aural Alarm | Pilot does not perceive advisory. |
| Manual Sensitivity Level Switch | Wrong Sensitivity Level selected. Missed RA (Level 1 or 2). Unwanted RA (Level too high). Late RA (Level too low). Missed TA (Level 1). |
| Antenna or Cables | Same as receiver, transmitter. |
| Partial Failure of Directional Antenna or Angle Receiver. | Incorrect bearing in TA. Missed TA, RA. Dropped tracks. |

## MODE-S TRANSPONDER FAILURES

| FAILURE | WORST POSSIBLE EFFECT(S) |
| --- | --- |
| Receiver | Own TCAS not seen by Threat TCAS. Maneuver Coordination cannot be completed. Ground Sensitivity Level Message not received. |
| Transmitter | Own TCAS not seen by Threat TCAS. Maneuver Coordination cannot be completed. |

## INCORRECT INPUT DATA

| INCORRECT DATA | WORST POSSIBLE EFFECT(S) |
| --- | --- |
| Threat Range, Altitude | Missed RA. Incorrect RA. Incorrect position on TA. No TA. TA not displayed due to incorrect low priority. |
| Threat TCAS-II Equipage | RA not coordinated. |
| Threat Crosslink Request | No crosslink sent. |
| Threat Mode-S Address | No track. Missed RA. |
| Threat Sensitivity Level | Late RA. |

| | |
|---|---|
| Threat Altitude Reporting Status | Missed RA. No altitude displayed on TA. |
| Threat Bearing | Incorrect position on TA. |
| Own Sensitivity Level | Same as Manual Sensitivity Level Switch. |
| Sensitivity Level Command From Mode-S | Same as Manual Sensitivity Level Switch |
| Own Magnetic Heading | Incorrect bearing sent in crosslink. |
| Own Barometric Altitude | Incorrect RA. Missed RA. Incorrect relative altitude in TA. |
| Own Radar Altitude | Wrong sensitivity level. Missed or late TA, RA. Threat incorrectly declared on ground. Missed TA, RA. "Descend" RA incorrectly converted to "Don't Climb." |
| Own Radar Altitude Missing | RA descends TCAS into terrain. Unwanted TA, RA against threat on ground. Wrong sensitivity level. Missed or late TA, RA. |

| | |
|---|---|
| Own Altitude Rate | Wrong RA (only for few seconds when TCAS initialized). |
| Coordination data: | |
| Threat ID | Uncoordinated RA selected. |
| LCK bit | Coordination with third TCAS may be delayed 0.1 second. |
| Advisory complement | Incorrect RA selected. |
| Threat Maximum airspeed | Late track. Late TA, RA. |
| Mode-S Threat On-Ground Status | Missed TA, RA. Alarm against threat on ground. |

# APPENDIX G
## EXTENDED BRANCHES OF THE TCAS FAULT TREE

There are 20 events in the fault tree which are TCAS-related and which are treated in further detail here. They are represented in Figures 7-2 and 7-3 by the events with transfer symbols (triangles) beneath them. The following listings are a tabular form of these extended branches. To avoid excessive duplication, branches similiar to others are not shown; reference will be made to the branch that is the same in general form. Branches were written without the fault parameters being explicitly defined. For instance, altimetry error will be listed as a cause of failing to satisfy threat advisory criteria, but the exact nature of that altimetry error (error less than 100', for example) will not be listed. This allows some branches on the unresolved NMAC side of the tree to double as branches on the induced NMAC side of the tree.

The following pages represent the extended development for these faults:

- TCAS Does Not Display a Traffic Advisory (Event 7-376)
- TCAS Does Not Display a Resolution Advisory (Event 5-420)
- TCAS Displays a Resolution Advisory, but Not in Time to Avoid the NMAC (Event 5-430)
- TCAS Displays a Resolution Advisory Which the Pilot Does Not Follow (Event 5-440)

- TCAS Displays a Resolution Advisory Which is Inadequate to Avoid the NMAC (Event 5-450)

- TCAS Displays a Resolution Advisory Which Will Lead to NMAC (Event 6-670)

- Traffic and Proximity Advisories (If Any) Do Not Show the Instruction/Maneuver is Incorrect (Event 8-733)

- TCAS Displays a Resolution Advisory Which Would Avoid the NMAC Except that the Threat Maneuvers (Event 5-950).

The extended development of some other faults follows that of one of those listed above, with different values in the probabilities. These faults, along with the ones they are patterned after follows below:

- No Traffic Advisory Is Displayed (Event 9-688) - Event 7-376

- Aircraft That Is a Threat Is Not Displayed (Event 9-725) - Event 7-376

- TCAS Is Not Displaying a Preventive RA Against the Maneuver (Event 6-745) - Event 5-420

- Aircraft That Is a Threat is Not Displayed (Event 8-794) - Event 7-376

- Traffic and Proximity Advisory Shown Does Not Show the Instruction Is Incorrect (Event 8-797) - Event 8-733.

- TCAS Does Not Display a Resolution Advisory (Event 5-910) - Event 5-420

- TCAS Displays a Resolution Advisory but Not in Time to Avoid NMAC (Event 5-920) - Event 5-430

- TCAS Displays a Resolution Advisory Which the Pilot Does Not Follow (Event 5-930) - Event 5-440

- TCAS Displays a Resolution Advisory Which Will Not Avoid the NMAC (Event 5-940) - Event 5-450

Extended development of event 7-398 (Pilot Did Not Avoid NMAC Based on Information Provided By the TCAS TA Display) and event 8-771 (Pilot Selects an Inappropriate Maneuver Based on the TCAS TA Display) was not done, as they are human factors-dependent faults. A branch for event 5-960 (TCAS Does Not Display an "Advisory Not OK") was not completed; the failure rate for the fault was assumed to be 1.0.

In the branches that follow, events are assigned a decimal fraction of the event they fall under (thus, event 376.2111 is a sub-event of event 7-376). The number of places assigned in that decimal fraction indicates how far down in the development the sub-event is. Any sub-event containing the full decimal of another (for example, 376.2111 contains 376.211, 376.21, and 376.20) is a subevent, or cause, of that event. All sub-events are connected by OR gates unless AND is specified.

376 TCAS does not display a traffic advisory

376.10 TCAS unit is not providing Traffic Advisories

376.11 Self-monitor shuts down TCAS unit

376.12 Sensitivity level set such that no TAs are provided

376.121 Pilot sets sensitivity level manually

376.122 Mode S ground sensor sets sensitivity level

376.20 No TA inputs are provided to the display

376.21 No traffic advisory is generated by the logic

376.211 Inputs do not satisfy threat criteria

376.2111 Surveillance does not provide a track which passes range test

376.21111 Surveillance does not pass adequate track to the logic

376.211111 Threat is non-Mode C aircraft

376.211112 Surveillance failure

376.21112 Surveillance fault causes incorrect range/range rate to be calculated

376.2112 Altitude reporting causes threat not to be judged a threat

376.21121 Threat is altitude-encoding aircraft AND

376.21122 Threat is judged not to be threat by altitude tests

376.211221 Threat is judged to be on ground

376.211222 Threat is judged to pass with > ZTHR separation

376.212 Undetected logic design flaw

376.213 Logic is coded incorrectly

376.214 Processing hardware fails

376.22 Processor - display connectors fail

376.30 Display limitation prevents display of threst

376.31 Multiple threats cause this one to be eliminated

376.32 Intruder overlaps own-aircraft symbol

376.40 Other function preempts display

376.50 Display hardware fails

- 420 TCAS does not display a Resolution Advisory
  - 420.10 TCAS unit is not providing RAs
    - 420.11 Self-monitor shuts down the TCAS unit
    - 420.12 Sensitivity level set such that no RAs are displayed
      - 420.121 Own altitude < 500 feet AGL
      - 420.122 Pilot selects sensitivity level < 4 manually
      - 420.123 Mode S uplink selects sensitivity level < 4
  - 420.20 No RA inputs are provided to the display
    - 420.21 No RA is generated by the logic
      - 420.211 Inputs do not satisfy RA criteria
        - 420.2111 Surveillance puts threat outside corrective RA position
          - 420.21111 Surveillance does not pass adequate track to the logic
            - 420.211111 Threat is non-Mode C aircraft
            - 420.211112 Surveillance failure
          - 420.21112 Surveillance error causes incorrect range/range rate to be calculated
        - 420.2112 Altitude reports put threat outside corrective RA position
          - 420.21121 Altitude errors put threat on ground
            - 420.211211 Uneven terrain
            - 420.211212 Intruder altitude error
            - 420.211213 Own Mode C altitude error
            - 420.211214 Own radar altimeter error
          - 420.21122 Altitude errors put threat in non-threat position
            - 420.211221 Own altitude error
            - 420.211222 Intruder altitude error
        - 420.2113 Intruder maneuver causes logic to delay RA beyond CPA
      - 420.212 Undetected logic design flaw
      - 420.213 Logic is coded incorrectly
      - 420.214 Processing hardware failure
    - 420.22 Processor-display connectors fail
  - 420.30 Display is preempted by other function
  - 420.40 Display hardware fails

430 TCAS displays an RA, but not in time to avoid NMAC

430.10 RA is delayed beyond time when maneuver can avoid NMAC

430.11 Conflict was created late

430.111 Own aircraft's motion created the conflict

430.112 Intruder aircraft's motion created the conflict

430.12 TCAS was enabled to issue resolution advisories in the midst of the conflict

430.121 Own aircraft in a conflict when TCAS enabled to issue RAs AND

430.122 TCAS enabled to issue RAs

430.1221 TCAS was just turned on in any 25 second period

430.1222 Own altitude increases to the point where RAs are enabled

430.1223 Mode S ground station enables RAs

430.1224 Pilot switches sensitivity level to enable RAs

430.13 TCAS acquired track in the midst of a conflict

430.131 Own aircraft in a conflict when TCAS acquired track AND

430.132 TCAS acquires track late

430.1321 Aircraft previously judged "on ground" now judged "in air"

430.1322 Intruder transponder just turned on

430.1323 Interference - limiting feature previously eliminated threat

430.1324 Intruder motion not within limits expected by Mode S surveillance

430.1325 Surveillance acquired late

430.14 Low firmness delays RA

430.141 Altitude credibility tests rejected reports

430.1411 Noisy surveillance data

430.1412 Stuck Mode C bit

430.1413 Intruder acceleration exceeds that expected

430.142 Intruder was perceived to be maneuvering

440 TCAS displays a Resolution Advisory which the pilot does not follow
- 440.10 Pilot does not execute the RA at all
  - 440.11 Crew does not perceive RA alarm
    - 440.111 Inadequate alarm design
    - 440.112 Crew is preoccupied
  - 440.12 Crew does not believe RA is correct
  - 440.13 Pilot must clear his airspace before maneuvering, but cannot
    - 440.131 Pilot cannot clear his airspace due to visibility (IMC, glaring sun, . . .)
    - 440.132 Pilot can clear his airspace (good VMC) but is unable
- 440.20 Pilot executes the RA, but inadequately
  - 440.21 Pilot stops before RA is removed
  - 440.22 Pilot continues beyond point RA is removed
  - 440.23 Pilot delays execution beyond time allowed

450 TCAS displays a Resolution Advisory which does not avoid the NMAC

450.10 TCAS is not shut down by self-monitor or sensitivity level AND

450.20 TCAS generates for display a Resolution Advisory which will not avoid the NMAC

450.21 Own TCAS generates an incorrect RA

450.211 RA is removed before aircraft is out of NMAC

450.2111 RA is given with incorrect sense and removed before altitude crossing +100'

450.2112 RA is given with correct sense and removed before aircraft is out of NMAC

450.212 Standard vertical rate is insufficient to achieve 100' separation

450.22 TCAS receives (via coordination link) an incorrect RA complement

450.221 Threat is TCAS-II equipped

450.222 Threat generates an incorrect RA

670 TCAS displays a Resolution Advisory which will lead to NMAC

- 670.10 TCAS is not shut down by self monitor or sensitivity level AND
- 670.20 TCAS generates for display an RA which will lead to NMAC
    - 670.21 Altitude error causes wrong sense RA which leads to NMAC
        - 670.211 Wrong sense RA is choosen AND
        - 670.212 Pilot stops following RA within 100 feet of threat
            - 670.2121 RA is removed within 100 feet of threat due to altimetry error
            - 670.2122 RA is removed before NMAC; pilot follows it until within 100' of threat
            - 670.2123 RA is removed after altitude crossing; pilot stops following it within 100' of threat, before it is removed
    - 670.22 C-bit error causes incorrect RA to be generated
    - 670.23 RA based on apparent trajectory is thwarted by intruder maneuver
    - 670.24 False track causes spurious RA which leads to NMAC with real aircraft
        - 670.241 False track causes spurious RA AND
        - 670.242 Spurious RA leads to NMAC with real aircraft

733 Traffic and proximity advisories do not show the instruction is incorrect
733.10 TCAS did not display the proximate aircraft own will maneuver into
733.11 No proximity advisory inputs are provided to the display
733.111 No TA is displayed
733.1111 No TA should be displayed
733.1112 No TA is displayed when one should be (Continue with tree for event 376)
733.112 TA is displayed but proximate aircraft is not
733.1121 No proximity advisory should be displayed
733.1122 Proximity advisory should be displayed but is not
733.11221 Inputs do not satisfy proximity advisory criteria
733.112211 Surveillance does not pass a track to the logic that is within proximity range
733.1122111 Surveillance does not pass adequate track to logic
733.11221111 Threat is non-Mode C aircraft
733.11221112 Surveillance failure
733.1122112 Surveillance provides incorrect range
733.112212 Altitude reports pass a relative altitude that does not satisfy proximity criterion
733.1122121 Threat is Mode C aircraft AND
733.1122122 Threat is judged not proximate
733.11221221 Threat is judged "on the ground"
733.11221222 Threat is judged to be 1200' away vertically
733.11222 Undetected logic design flaw
733.11223 Logic is coded incorrectly
733.11224 Processing hardware fails
733.1123 Display limitation prevents display of the proximate aircraft
733.11231 Multiple aircraft cause this one to be eliminated
733.11232 Proximate aircraft overlaps own-aircraft symbol
733.12 Display hardware failure
733.20 Displays shows the proximate aircraft but in the wrong location
733.21 Displays its bearing incorrectly
733.22 Displays its range incorrectly
733.23 Displays its relative altitude incorrectly

950 TCAS displays an RA which would avoid NMAC except that the threat maneuvers

- 950.10 Threat maneuvers after RA is issued and neither the pilot nor TCAS corrects
  - 950.11 Threat maneuvers sufficient to counter RA AND
  - 950.12 Neither the pilot not TCAS recognizes situation and corrects
    - 950.121 Pilot does not recognize situation
      - 950.1211 Does not see it (visual)
        - 950.12111 IMC (if RAs allowed in IMC)
        - 950.12112 Assumes RA o.k.
        - 950.12113 Cannot acquire threat
      - 950.1212 Does not see it from TA display
        - 950.12121 Not monitoring the display
        - 950.12122 Display does not show it
        - 950.12123 Cannot tell that display shows it
      - 950.1213 TCAS does not tell pilot that advisory is not adequate
        - 950.12131 TCAS does not issue "Advisory not OK"
        - 950.12132 Pilot fails to perceive alarm
    - 950.122 Pilot becomes aware of situation, but cannot correct
      - 950.1221 Not enough time to maneuver
      - 950.1222 Cannot devise a maneuver
- 950.20 Other aircraft (different than threat) involved in NMAC

APPENDIX H

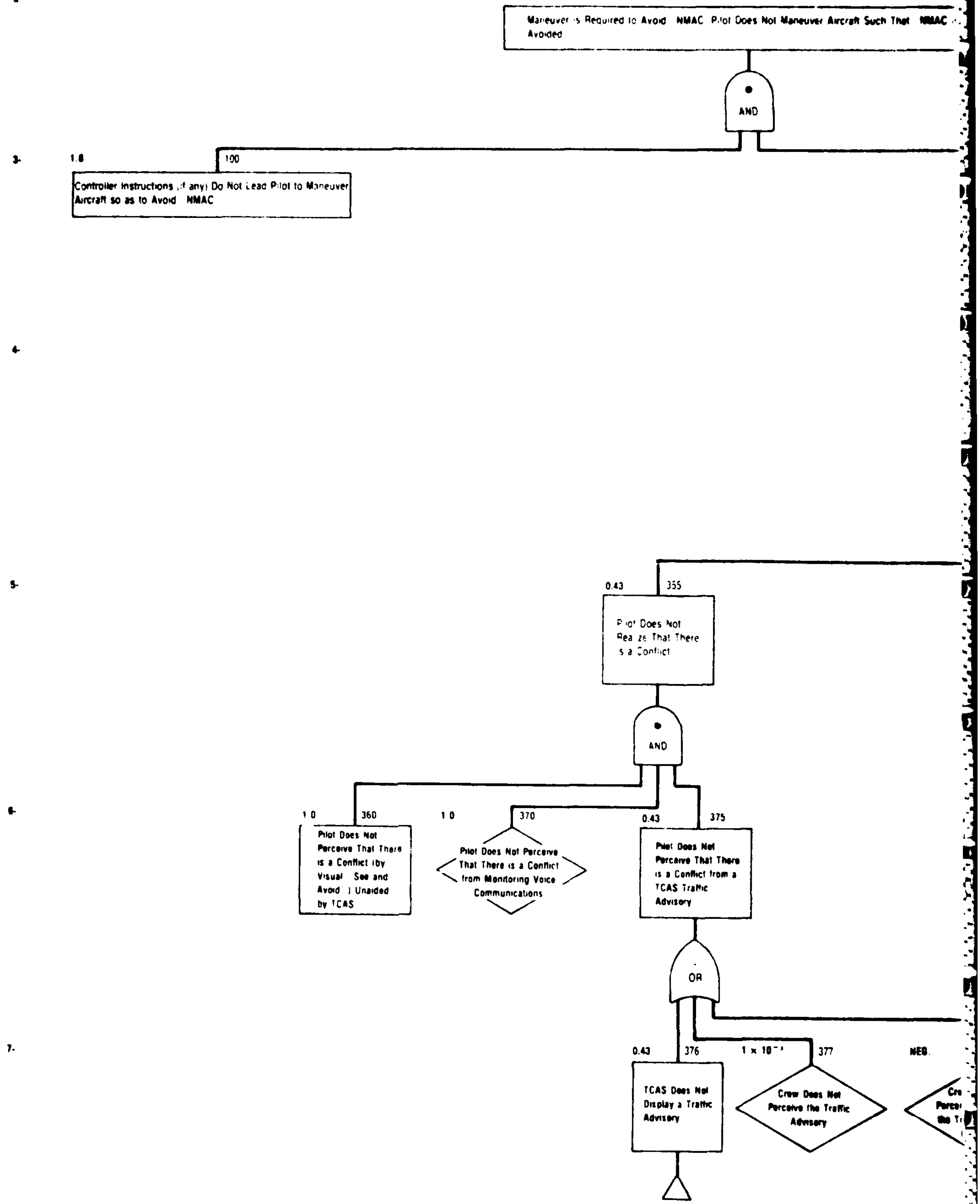
CALCULATION OF FAULT TREE PROBABILITIES FOR INTERMEDIATE EVENTS

In Figure 7-5 of Section 7, the probabilities of all intermediate events were furnished for completeness. As many events in the tree are not independent of each other, the calculations of their probabilities do not proceed in a straightforward manner (i.e., one cannot simply add at "OR" gates and multiply at "AND" gates). This appendix documents the means by which the intermediate events were estimated for the 000 Branch of the tree (Unresolved NMAC).

## H.1 The 000 Branch (Unresolved NMAC)

Figure H-1 shows the reduced 000 branch of the fault tree. The method by which the probability of event 3-300 was obtained is shown in Section 7; in this appendix, we will document the method by which the probabilities of events 4-350, 4-410, 5-380, 6-390, and 6-395 were obtained; the rest of the events with probabilities attached follow the straightforward rules for "AND" and "OR" gates.

Events 6-390, 6-315, and 5-380. Because all gates below event 5-380 are "OR" gates, the fault tree below the event can be rearranged so that there is one "OR" gate beneath the event with branches to events 6-385, 7-391, 7-392, 7-396, 7-397, and 7-398. One can then proceed, via a single mathematical operation at the one "OR" gate, to calculate the probability of event 5-380. In addition, to facilitate the human factors analysis, failure events 7-392 and 7-396 have been combined into a single event with failure probability VNA. One should also note the failure probability assigned to event 7-397 is 0.0. As a consequence, we can write the set expression for event 5-380 as




H-3

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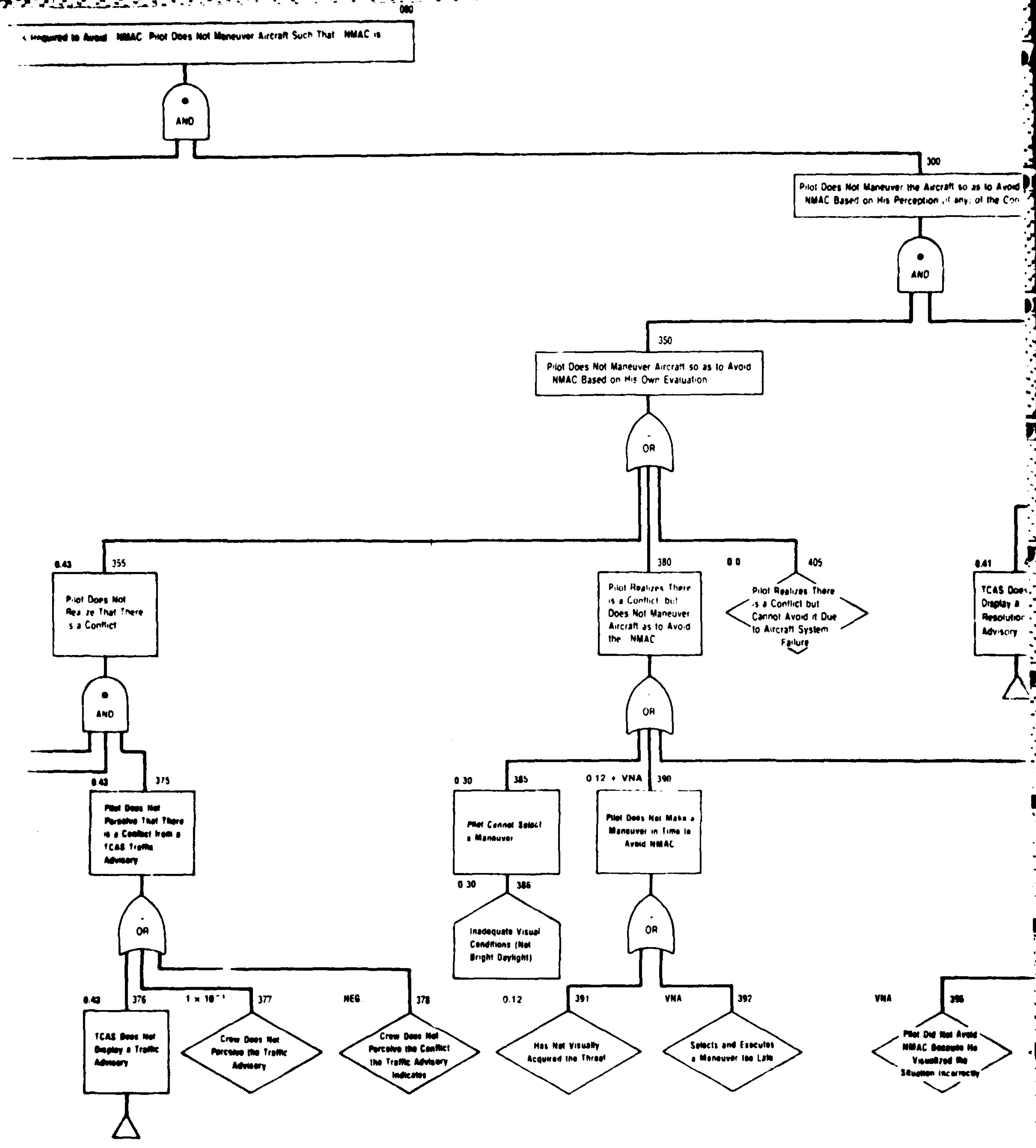


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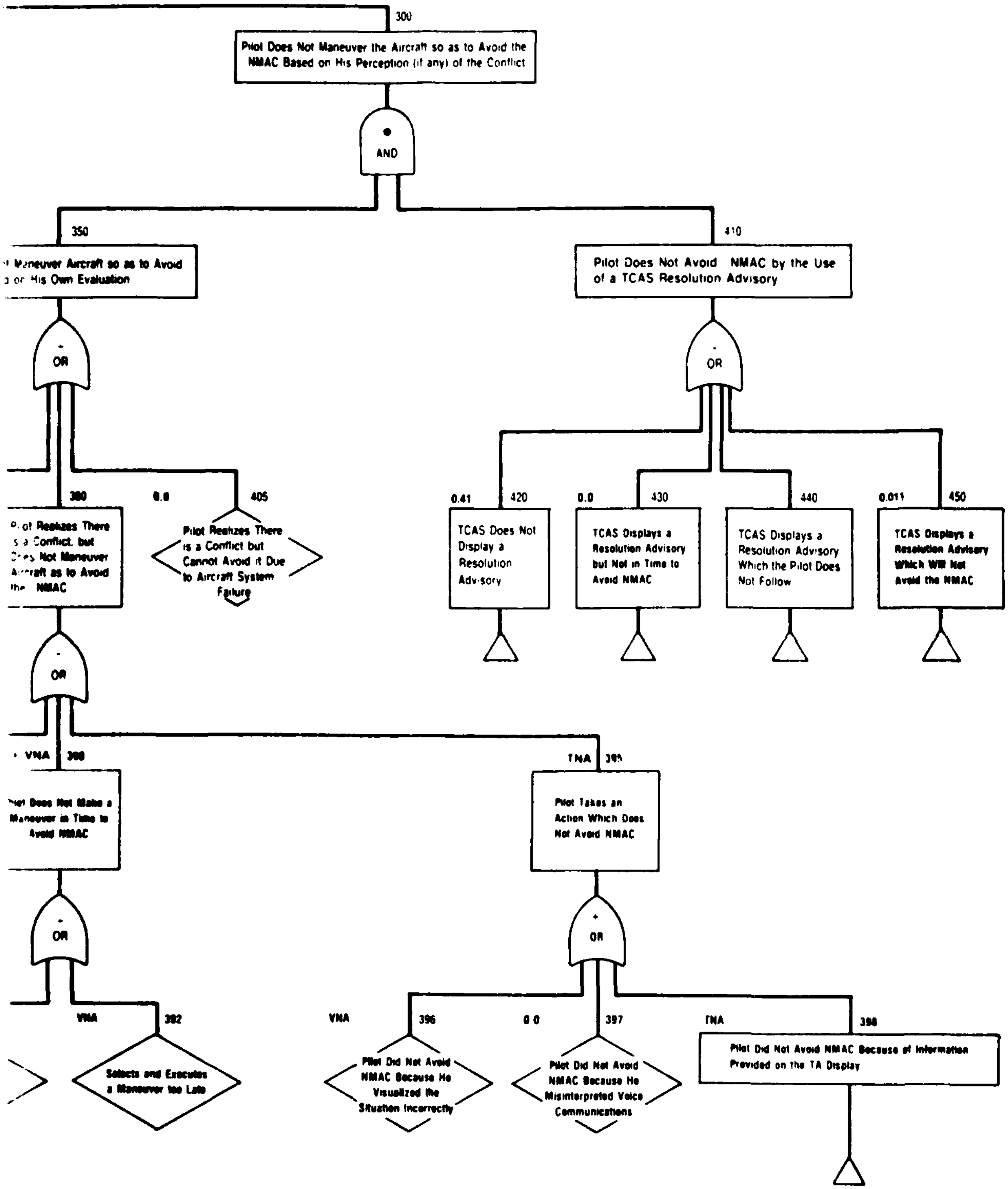


**FIGURE H-1**
**000 BRANCH OF FAULT TREE**
**(UNRESOLVED NMAC)**



3

(5-380) = (6-385) U (7-391) U (7-392,7-396) U (7-398)

and proceed to evaluate the probability of event 5-380.

Event 5-380, Pilot Realizes There Is a Conflict but Does Not Maneuver Aircraft So as to Avoid the NMAC, contains a precondition for its occurrence. The precondition is implied by the words "Pilot Realizes There Is a Conflict," which is the opposite event to 5-355, Pilot Does Not Realize There Is a Conflict. Event 5-380 thus includes the requirement that a TA is displayed (the opposite of the failure comprising event 5-355). The failure mechanisms listed below event 5-380 are developed as conditional events; i.e., they are failures given the presence of a TA. One multiplies these conditional probabilities by the probability of receiving a TA in order to obtain the overall probability of the occurrence of event 5-380.

The conditional probabilities of the events below 5-380 are obtained as follows:

- Event 6-385 (Pilot Cannot Select a Maneuver). This event is the occurrence of inadequate visual conditions. Visual conditions are independent of the presence of a TA; the conditional probability of inadequate visual conditions given the presence of a TA is thus simply the probability of inadequate visual conditions, or .30.

- Event 7-391 (Pilot Has Not Visually Acquired the Threat). Section 6 provides the probability of not visually acquiring a threat by 15 seconds prior to CPA, given a TA and good visual conditions, .17. We can convert this to the conditional probability of no visual acquisition given



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a TA by multiplying by the probability of good visual conditions (1-.30, or .70) to obtain the result: .12.

- Events 7-392 and 7-396, Pilot Does Not Avoid NMAC (or is Too Late) Because He Visualized the Situation Incorrectly. A human factors failure probability, VNA, was defined as the probability of not avoiding the threat given the threat has been acquired. The probability that the pilot does not avoid the threat given a TA is this probablity, VNA, times the probability of visual acquisition given the TA. The latter probability is the probability that events 6-385 and 7-391 above have not occurred, or 1 - (.30 + .12) = .58. Thus, the probability of acquiring but not avoiding, given a TA, is .58 (VNA).

- Event 7-398, Pilot Did Not Avoid NMAC Based on Information Provided In the TCAS TA Display. We have defined a human factors failure for this event, TNA, which is the probability the pilot does not avoid the NMAC due to a TA and is conditional upon receiving the TA.

These four probabilities can be combined to obtain the conditional probability of event 5-380 given the presence of a TA. The first three events (6-385, 7-391, and 7-392/6) are mutually exclusive; their probabilities can be summed to obtain the probability of any of the three events occurring, or .42 + .58 (VNA). The fourth event is independent of the first three (given a TA). We can combine it with the previous three events under the rules for independence:

(.42 + .58 (VNA)) + TNA - [.42 + .58 (VNA)]TNA

or

.42 + .58 (VNA) + .58 (TNA) - .58 (VNA)(TNA)

Assuming (VNA) and (TNA) are no greater than 0.1, the product .61 (VNA)(TNA) will be at least two orders of magnitude lower than the rest of the expression and will be neglected.

This is the conditional probability that the pilot does not maneuver the aircraft given the presence of a TA. It is multiplied by the probability of receiving a TA, .57, to produce the probability of event 5-380, or

.24 + .33 (VNA + TNA)

Event 4-410. Events 5-440 and 5-450 also have preconditions for their occurrence; the requirement is that "TCAS Displays a Resolution Advisory..." We have, from Section 5.1.5 and Table 8-1, the conditional probability of event 5-450 (TCAS Displays an RA Which Is Inadequate to Avoid NMAC); it is .011. For event 5-440 (TCAS Displays a Resolution Advisory Which the Pilot Does Not Follow), the human factors failure rate RNF was defined as the probability of not following an RA, given one is present. Multiply each of these probabilities by the probability of receiving an RA, (1-.41 = .59), to obtain the overall probabilities of each; for 5-440, it is .58 RNF and for 5-450, .0065. Then sum the four probabilities of events 5-420 through 5-450 to produce the probability of event 5-410, or .42 + .58 (RNF).

# APPENDIX I

## CALCULATION FOR SENSITIVITY ANALYSIS

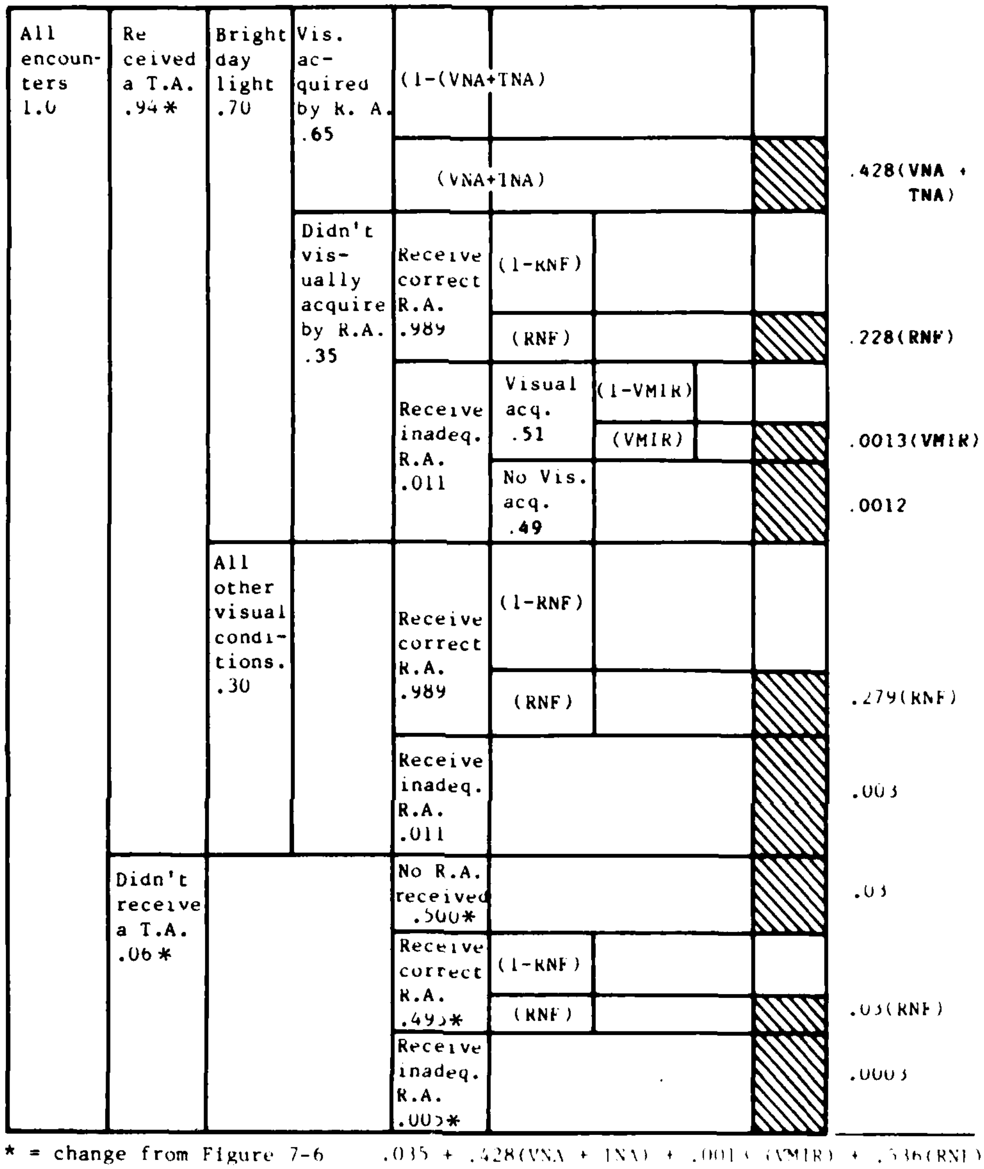
In Section 8 a sensitivity analysis was performed in which changes were made to underlying probabilities. The resulting changes in the probability of event 2-000 (unresolved NMAC) and event 2-500 (induced NMAC) were presented. This appendix describes the means by which those probabilities were calculated.

Recall from Section 7 that the probability of the top event is the sum of the probabilities of events 2-000 and 2-500. In turn, the probability of event 2-000 is that of 3-300 (Pilot Does Not Maneuver the Aircraft So As to Avoid NMAC Based on His Perception (If Any) of the Conflict); the probability of event 2-500 is that of event 4-650 (Pilot Maneuvers Aircraft Because of Instruction Provided to Him). The probability of these events was estimated using the diagrams of Figures 7-6 and 7-9. In this appendix, these types of diagrams will be used to show how the changes in probability were obtained. For most of the sensitivity tests (as listed in Table 8-1), a modification of Figures 7-6 and 7-9 will be provided along with the description of how they have changed.

### 1. Mode-C Equipage

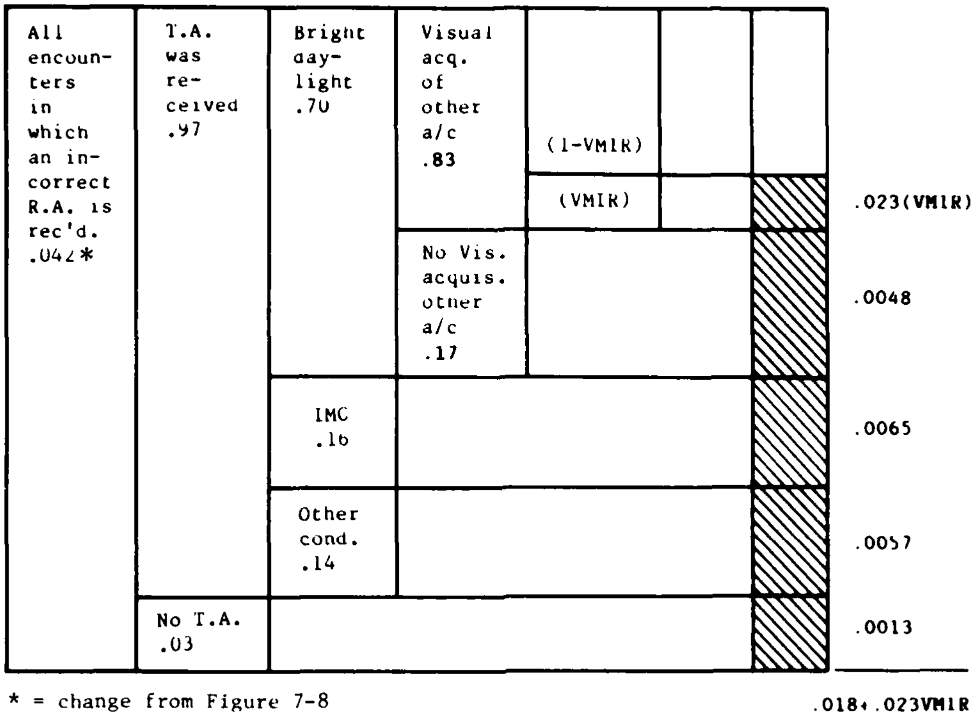
The first sensitivity test changes Mode C equipage to 100%. The diagrams which calculate the probabilities for events 3-300 and 4-650 are shown in Figures I-1 and I-2, respectively. Changed probabilities are highlighted by the asterisks.

Two changes can be seen for unresolved NMACs (Figure I-1). One is that the probability of receiving a TA has increased from .57 to .94




* = change from Figure 7-6

**FIGURE I-1**
**PROBABILITY OF EVENT 3-300**
**WITH FULL MODE-C EQUIPAGE**




* = change from Figure 7-8

**FIGURE I-2**
**PROBABILITY OF EVENT 4-650**
**WITH FULL MODE-C EQUIPAGE**

(thus, the probability of not receiving a TA has dropped to .06); also, given that no TA was received, the probability of not receiving the RA drops from .953 to .50. The result is an overall lowering of the probability of not resolving the NMAC to 3.5 percent.

This is accompanied, however, by an increase in induced NMACs (Figure I-2), due to an increase in the probability of receiving an RA which will lead to a critical NMAC (increased from .025 to .042). The result is an increase in from 1.1 percent to 1.8 percent for the probability of inducing an NMAC.

## 2. Surveillance Failures

This sensitivity test measures the impact of a change in surveillance failure. The diagrams for events 3-300 and 4-650 are shown in Figures I-3 and I-4. Those probabilities that change show two values; the first is for improved surveillance, the second for degraded surveillance.

For unresolved NMACs, two sets of probabilities change: 1) The probability of receiving a TA increases by .03 (or decreases by .02) with a corresponding decrease (increase) in the probability of not receiving a TA; 2) Given that no TA has been received, the probability that no RA is received increases (decreases) to .99 (.948).

## 3. Altimetry Error

This sensitivity test measures the impact of a 20% decrease (or increase) in GA altimetry error. The diagrams for events 3-300 and 4-650 are shown in Figures I-5 and I-6.

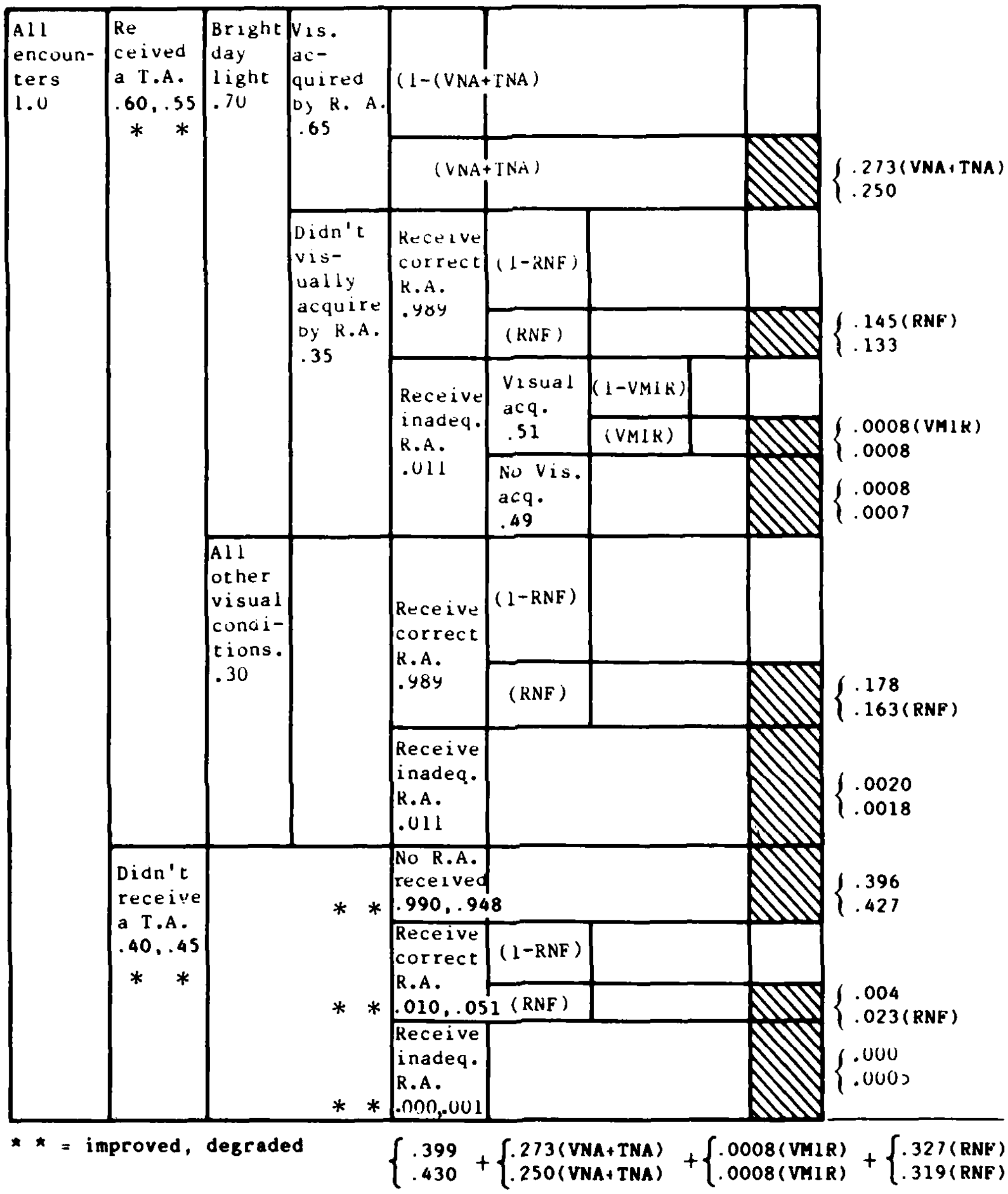



**FIGURE I-3**
**PROBABILITY OF EVENT 3-300**
**WITH SURVEILLANCE FAILURE CHANGES**

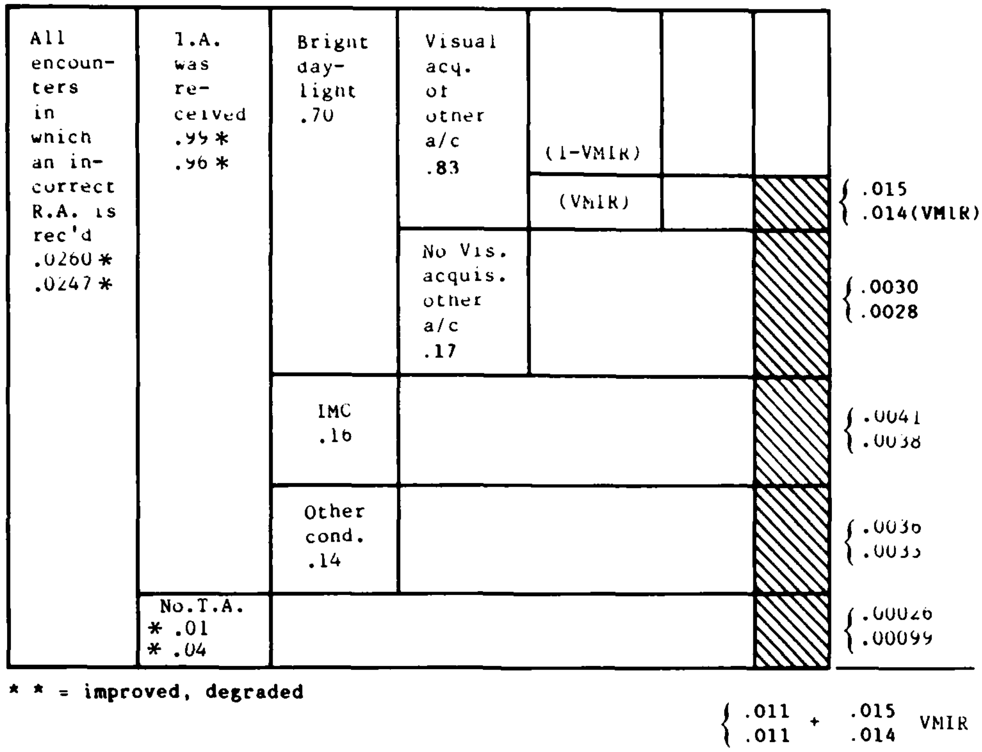



**FIGURE I-4**
**PROBABILITY OF EVENT 4-650**
**WITH SURVEILLANCE FAILURE CHANGES**

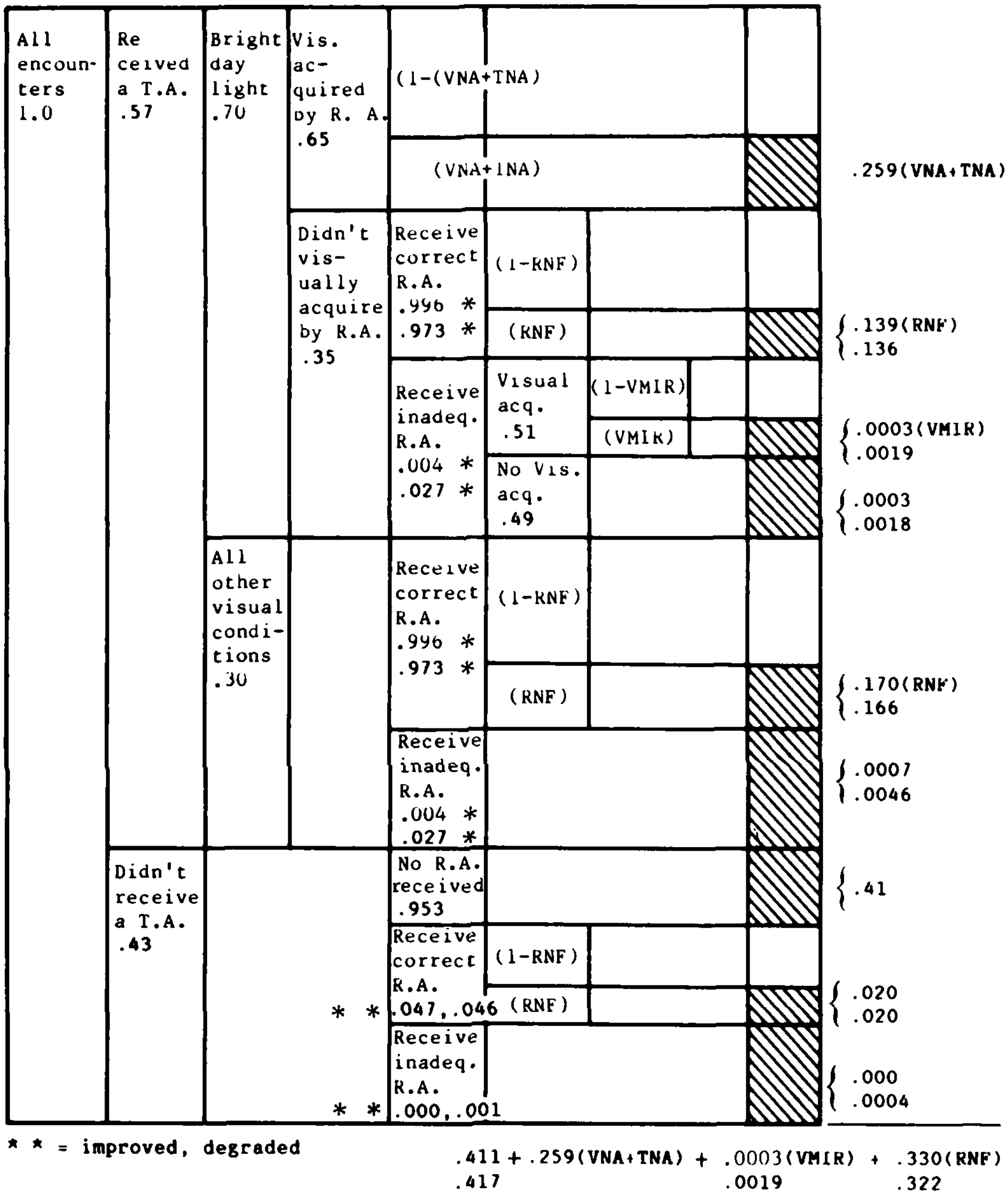



**FIGURE I-5**
**PROBABILITY OF EVENT 3-350**
**WITH ALTIMETRY ERROR CHANGES**

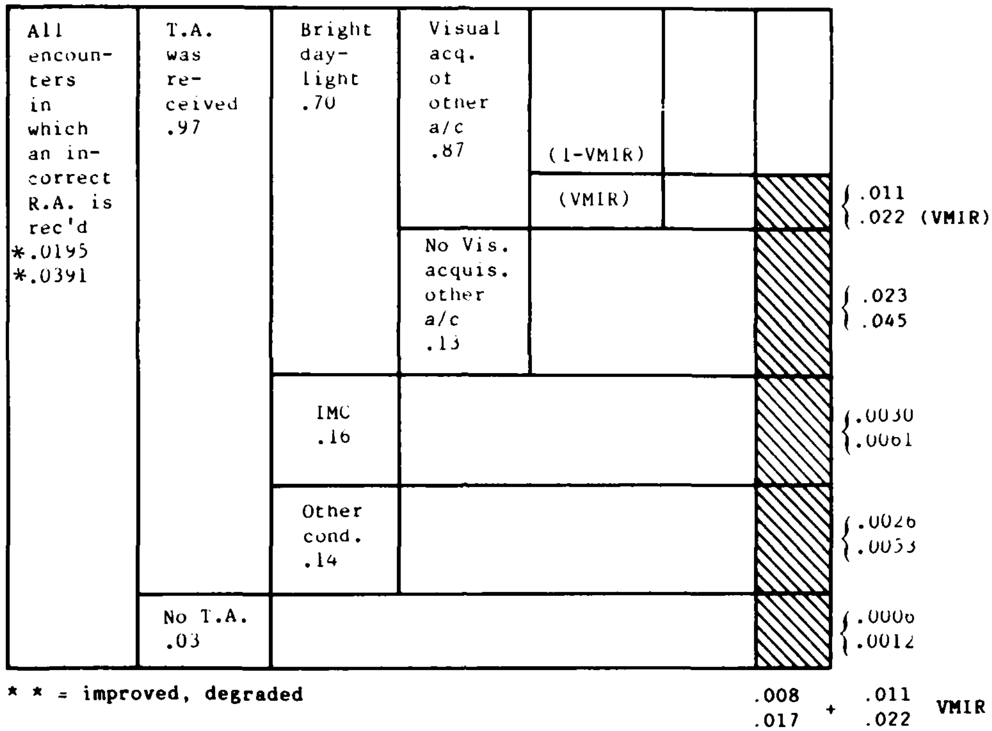



**FIGURE I-6**
**PROBABILITY OF EVENT 4-650**
**WITH ALTIMETRY ERROR CHANGES**

For both unresolved NMACs (3-300) and induced NMACs (4-650), altimetry error has no impact on the probability of a TA; its impact is to change the proportion of RAs that are inadequate to avoid NMAC from .011 to .004 (.027), and to change the probability of receiving an RA which will induce NMAC from .025 to .0195 (.0391).

4. Maneuvering Intruder Hazard

This sensitivity test measures the impact of a doubling or halving of failure probability due to sudden intruder maneuvers. This does not change the probability of an unresolved NMAC; the only change is for event 4-650 (induced NMAC). The means by which it is calculated is shown in Figure I-7. The failure rate that changes is the probability of receiving an RA which could lead to an NMAC.

5. Human Factors Failures

In this sensitivity test we have quantified the human factors failures represented as variables in the nominal case. A failure rate of 1 in 20 (.05) was tested as an estimate of the highest failure rate likely. To calculate the probabilities associated with these failures, the variables VNA, TNA, RNF, VMIR, and TNA are individually replaced with .05, multiplied by their coefficients, and summed to the nominal failure rates.

6. Non-Mode C Tracking

This sensitvity test measures the impact of receiving TAs for Mode A aircraft. This only changes the probability of an unresolved NMAC, it does not increase or decrease the probability of an induced NMAC. The diagram for event 3-300 is shown in Figure I-8. The probability of receiving an RA has not changed; however, the conditional probabilities of receiving an RA given the presence of a TA are lower, reflecting the fact that no RAs are being provided for

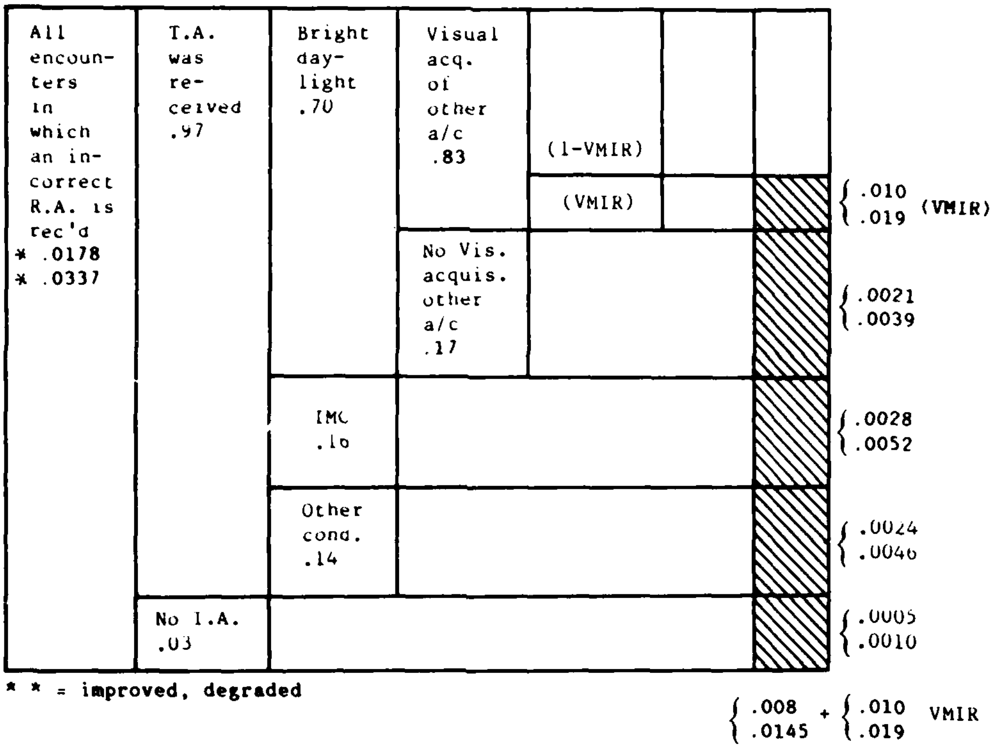



**FIGURE I-7**
**PROBABILITY OF EVENT 4-650**
**WITH MANEUVERING INTRUDER HAZARD CHANGES**

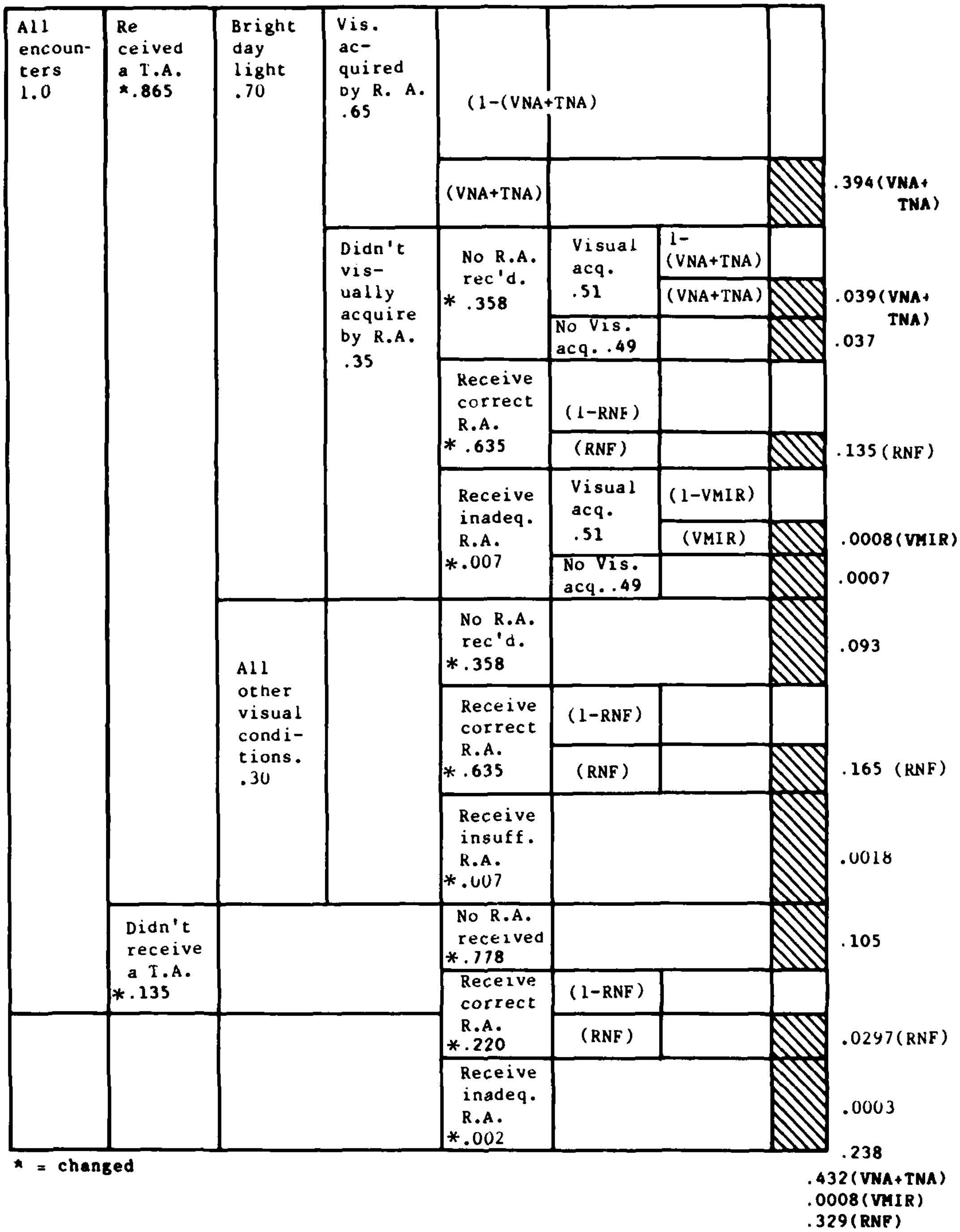



**FIGURE I-8**
**PROBABILITY OF EVENT 3-300**
**WITH NON MODE-C TRACKING**

Mode A aircraft. We have assumed the probability of visually acquiring a Mode A threat on near collision course is the same as that of a Mode C threat.

### 7. Visual Acquisition Ineffective

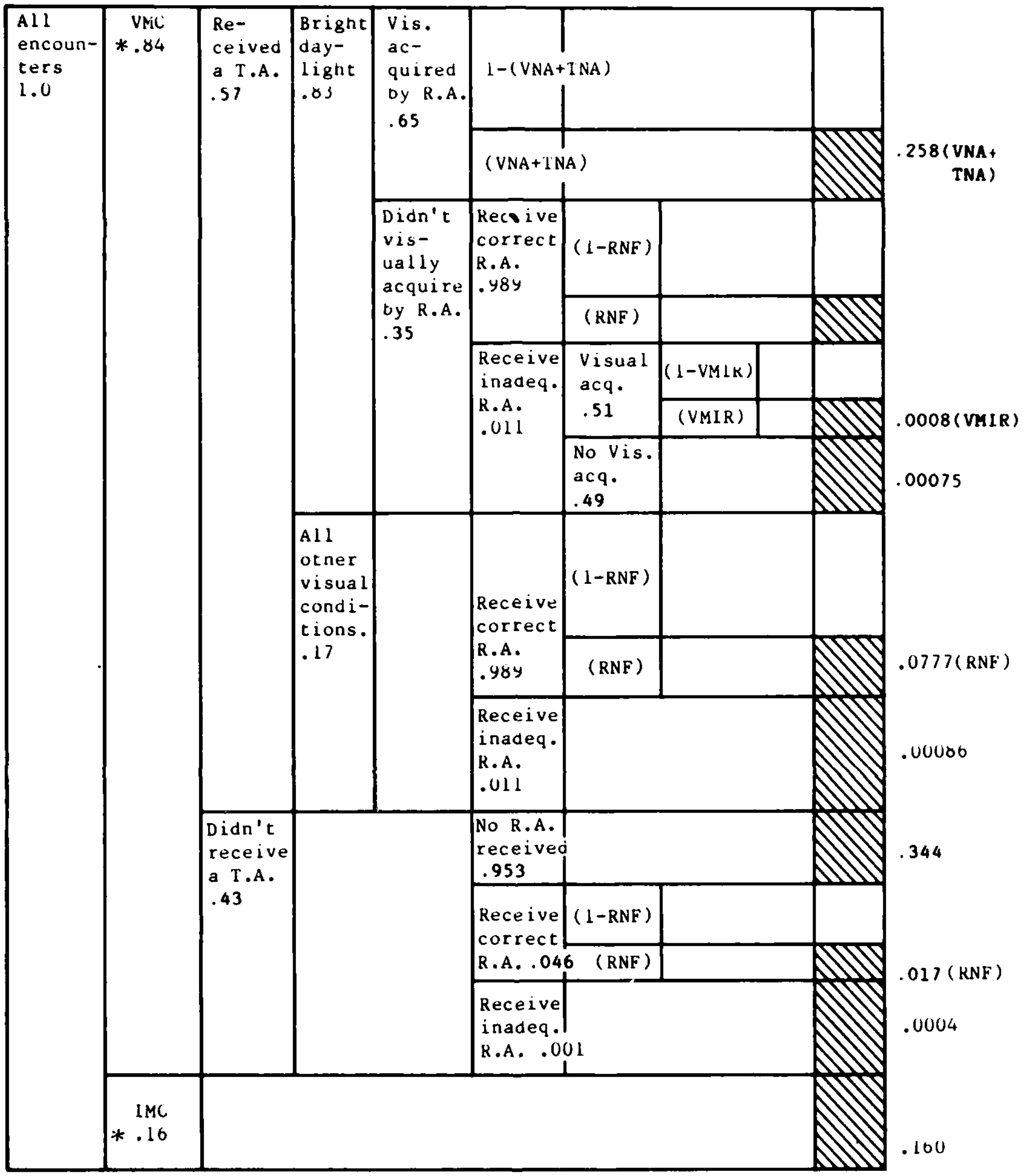
If visual acquisition as aided by the TA is not effective, then the only improvement that can be made in resolving NMACs is if a correct RA is issued. Thus, the probability of event 4-410 (Pilot Does Not Avoid NMAC By the Use of a TCAS TA), .42, is the probability that the NMAC is not resolved.

Likewise, without visual acquisition it is assumed that an incorrect RA would result in an NMAC; thus, the probability of event 5-660 (Pilot Is Issued an Instruction Which Will Lead to NMAC), .025, is the probability an RA will lead to an induced NMAC.

### 8. Do Not Follow RA in IMC

The impact of not following an RA in IMC is that in 16% of NMAC encounters, no action can be taken to resolve the NMAC (visual acquisition is assumed not possible and no TA will be followed). However, the number of RAs which would lead to an induced NMAC is reduced.

The diagrams for these cases are shown in Figures I-9 and I-10. In I-9, nominal failures are multiplied by .84, with the .16 probability of being in IMC contributing directly to the overall failure probability, as shown at the bottom of the figure. In I-10, however, we have removed from the failures for induced NMACs those that would have occurred in IMC, as shown by the lack of shading in the right column on the row where IMC occurs.




* = changed

.507
\+ .259(VNA+TNA)
\+ .0008(VMIR)
\+ .234 (RNF)

**FIGURE I-9**
**PROBABILITY OF EVENT 3-300**
**WITH NO RAs FOLLOWED IN IMC**

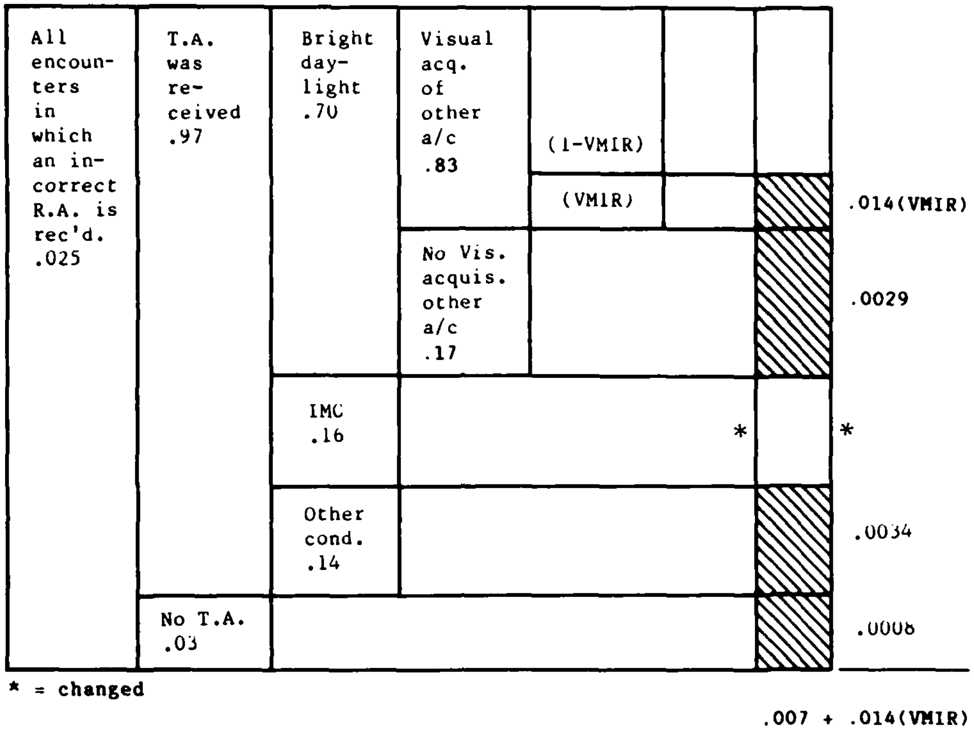



**FIGURE I-10**
**PROBABILITY OF EVENT 4-650**
**WITH NO RAs FOLLOWED IN IMC**

## 9. Exponential Altimetry Error Distribution

This sensitivity test measures the impact of the assumption that altimetry errors are Gaussian. In this test, we recomputed the probability of receiving an RA inadequate to avoid an NMAC (from .011 to .023) and of receiving an RA which will induce an NMAC (from .025 to .035). The diagrams for events 3-300 and 4-650 are shown in figures I-11 and I-12.

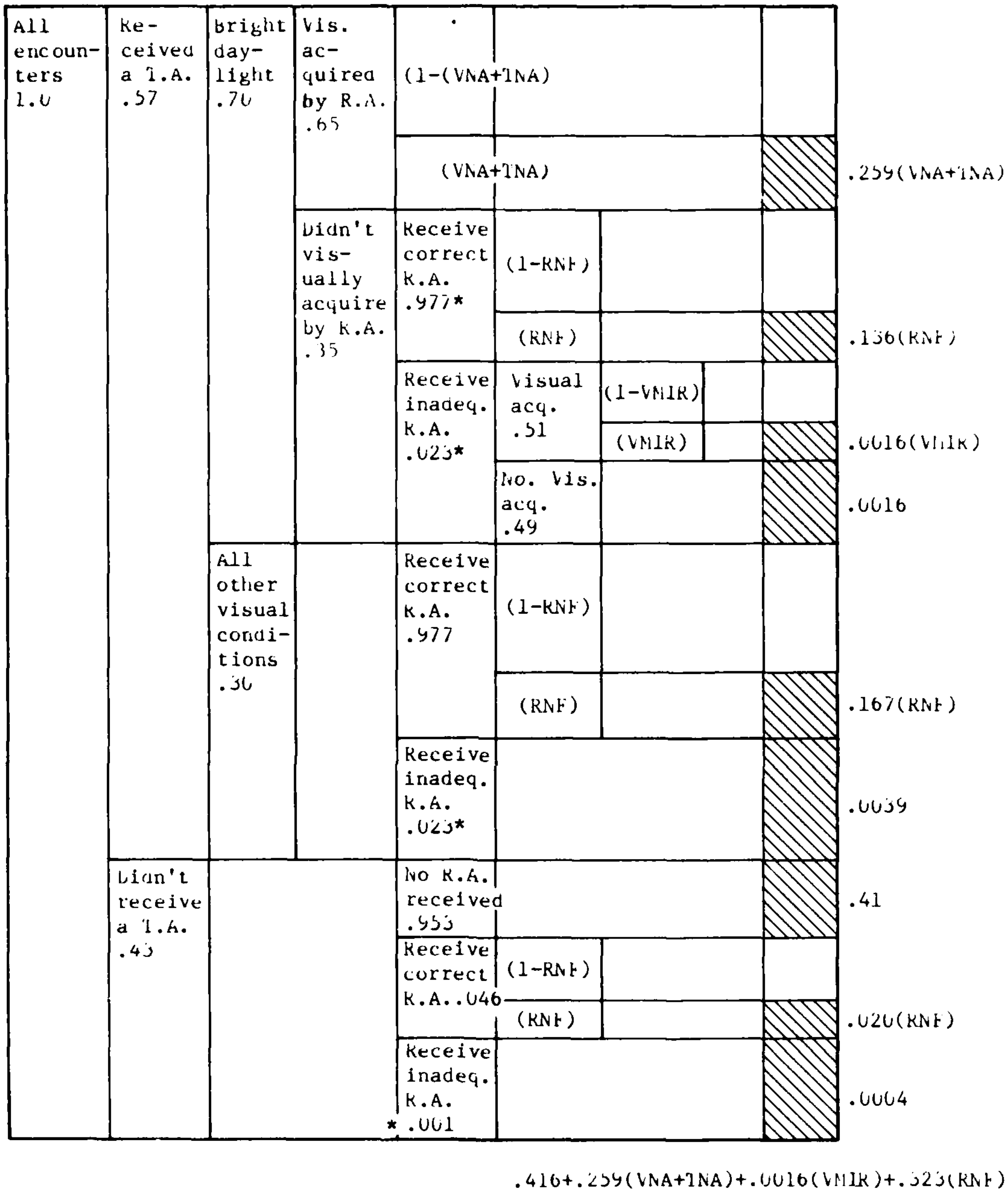



**FIGURE I-11**
**PROBABILITY OF EVENT 3-350 WITH EXPONENTIAL ALTIMETRY ERROR DISTRIBUTION**

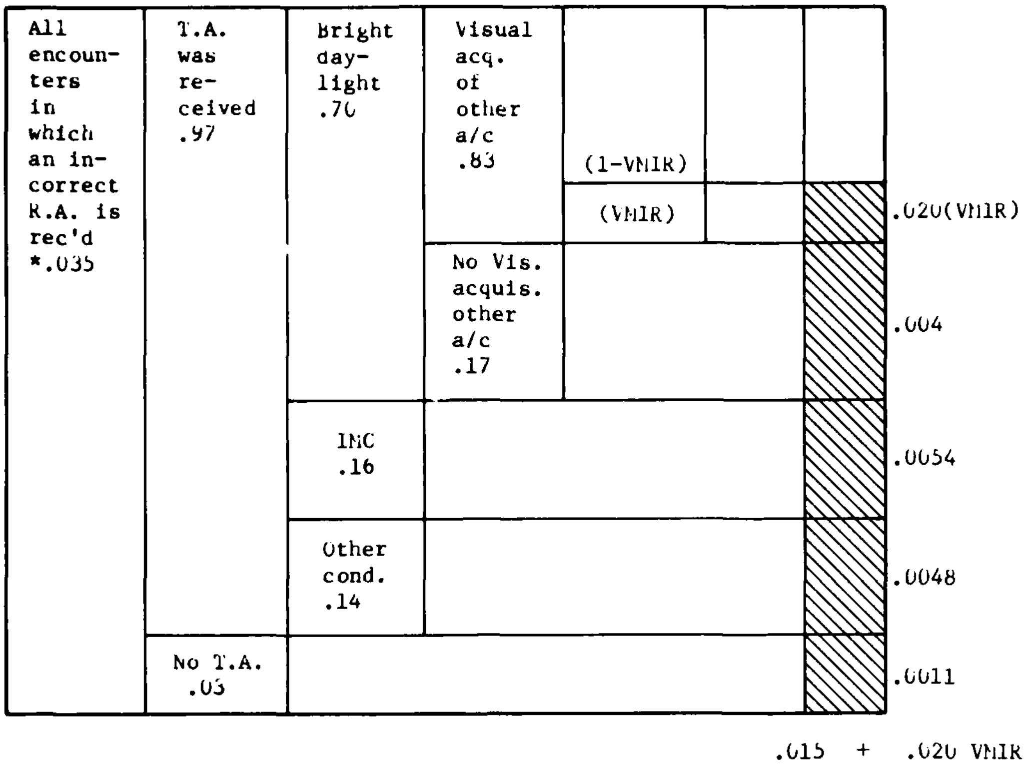



**FIGURE I-12**
**PROBABILITY OF EVENT 4-650 WITH EXPONENTIAL ALTIMETRY ERROR DISTRIBUTION**

## APPENDIX J

## GEOMETRIES LEADING TO

## ALTITUDE CROSSING ADVISORIES

This Appendix discusses the features of TCAS logic to support the analysis of Section 5.2.2 which determines for which encounters TCAS is potentially faked out by the intruder's maneuver. The threat's relative altitude and altitude rate determine the action taken by the TCAS logic.

Figure J-1 shows regions of different Detection and Resolution performance to the threat's relative altitude (A) and altitude rate (ADOT) at the time of sense selection. Every track falls into one of these regions. TCAS is assumed level. The lines on the figure are shown for the low-altitude region where Tau = 25 seconds, ALIM = 340 ft and ZTHR = 750 ft. For higher altitudes, the figure would appear similar, but scaled slightly differently (e.g., some diagonal regions would be wider).

First, this figure will be discussed to identify the regions in which an altitude-crossing sense is selected; the fake-out scenario can occur only in such a region. The bottom half-plane denotes the threat diverging vertically, ADOT GT 0. For tracks in region 1 ((A + ADOT * Tau) GT ZTHR), no advisory is given, since the projected separation exceeds the Vertical Miss Distance threshold. For tracks in region 2 (0 LT (A + ADOT * Tau) LT ZTHR), the sense that reinforces the separation is selected. In the top half-plane, ADOT is less than zero. Region 3 ((A + ADOT * Tau) GT ZTHR) corresponds to sufficiently large vertical separation (VMD greater than ZTHR) so that no

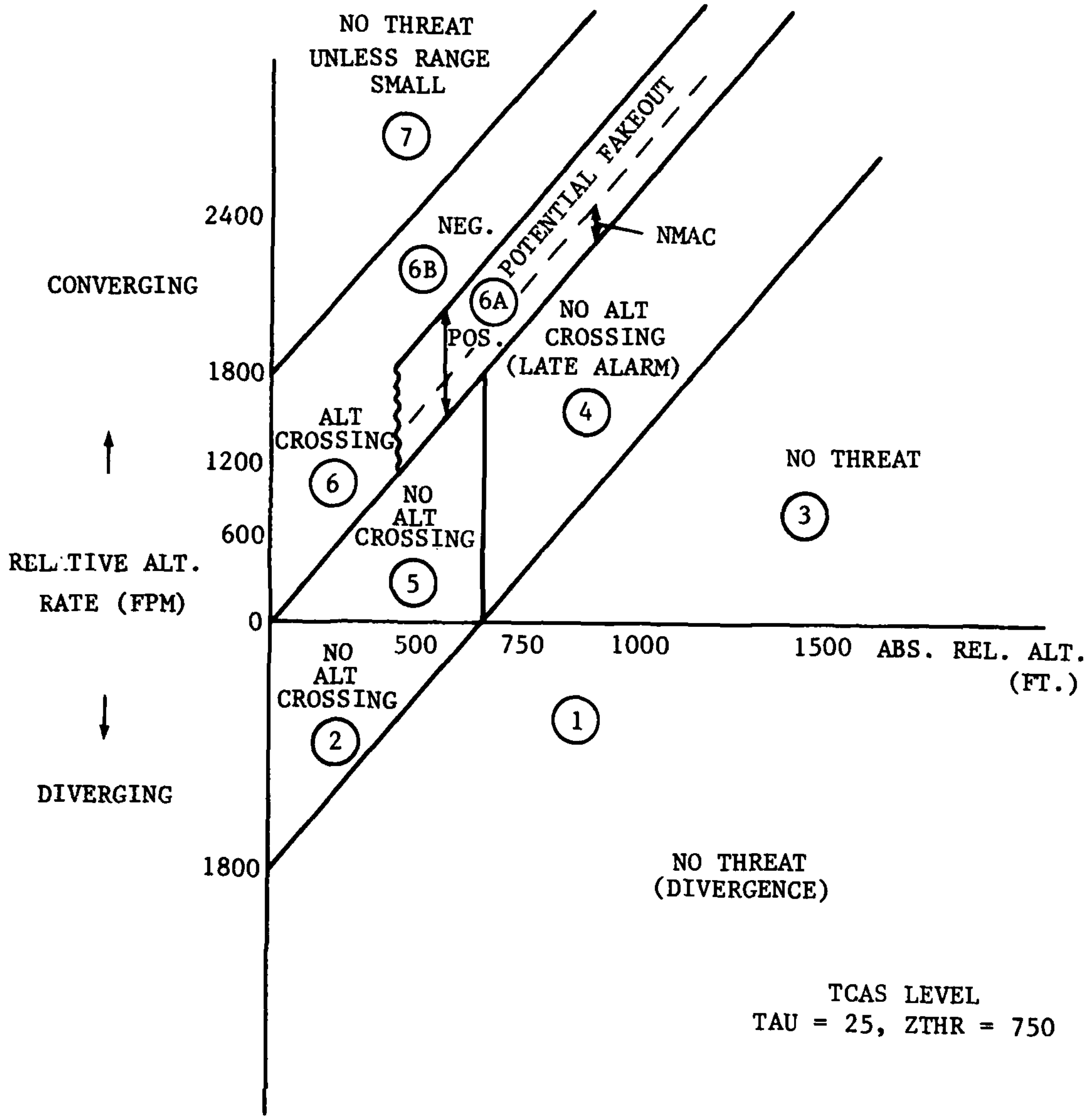



**FIGURE J-1**
**SUSCEPTIBILITY OF TCAS TO FAKE-OUT**

advisory is ever given. Even if the threat later converges at a higher rate, the advisory will surely begin in region 4. For tracks in region 4 (0 LT (A + ADOT * Tau) LT ZTHR and A GT ZTHR), vertical Tau is still above the alarm threshold, so that no alarm is generated at the "usual" time of range Tau passing its threshold (-(R-DMOD)/RDOT LT TRTHR). In this sense the advisory is "late", but no suggestion of decreased safety is meant. A threat initially in region 4 will later satisfy the altitude Tau threshold and cause a non-crossing sense to be selected.

For tracks in region 5 (0 LT(A + ADOT * Tau) LT ZTHR and A LT ZTHR), an immediate alert is selected. The low convergence rate gives the projected VMD the same sign as current separation. This causes a non-crossing sense to be selected. For tracks in region 6 (-ZTHR LT (A + ADOT * Tau) LT 0), the threat is projected to cross through TCAS' altitude by closest point of approach. Therefore, an altitude crossing sense is selected. This region is discussed further below. For tracks in region 7 ((A + ADOT * Tau) LT -ZTHR), the threat is projected to cross through TCAS' altitude, and pass vertically by more than ZTHR. Therefore, the Vertical Miss Distance test also eliminates this alert, unless the range is close enough that the Horizontal Miss Distance test keeps the alarm. In this case, the Critical Interval Logic should force a non-altitude-crossing sense. In the interest of upper-bounding the fake-out probability, this analysis will assume that no alert is given in region 7.

Region 6 is, therefore, the one leading to altitude crossings. In some of these cases, an intruder could potentially "fake-out" the TCAS. Region 6 may be further analyzed to relate altitude crossings to fake-out cases. When the relative altitude is small at initial alarm time (A less than about 500 ft; to the left of the wavy line), an intruder level-off cannot leave the intruder at TCAS' final altitude since TCAS attempts to achieve a separation of ALIM, nominally 340 ft for the 25 second Tau shown. If the intruder made such a level-off, TCAS would cross through the intruder's altitude despite the "wrong-way" sense.

The rest of region 6 can be divided into two subregions. When the Vertical Miss Distance (VMD) is less than ALIM, a positive advisory is generated. This is labeled subregion 6A (-ALIM LT (A + ADOT * Tau) LT 0). When VMD is more than ALIM but less than ZTHR, a negative advisory is generated. This is subregion 6B (-ZTHR LT (A + ADOT * Tau) LT -ALIM). In this subregion, the advisory does not tell the pilot to change altitude. If the intruder executes the "fake-out" level-off, the advisory briefly strengthens to positive, but soon changes to "Advisory Not-OK". (In simulations with 1/4 g level-off, the positive was displayed only 3 seconds.) With this sequence, the TCAS aircraft is unlikely to displace significantly toward the5Ontruder's final altitude. Thus, this case does not lead to a critical NMAC, although the initial sense choice later becomes wrong. It is thus concluded that the geometry combinations labeled region 6A constitute the potential fake-out scenarios.

# APPENDIX K

## AIRCRAFT ALTIMETRY DATA

This appendix identifies altimetry systems and their performance for two "classes" of these systems: Air Data Computer (ADC) corrected altimetry systems, as found on air carrier aircraft, and baseline, or uncompensated, altimetry systems, typical of general aviation (GA) aircraft. The altimetry systems of interest here are those arrangements of pneumatic, mechanical, or electrical devices which sense the ambient air pressure about an aircraft in flight and which transduce that pressure to either an altitude input to TCAS or to a Mode C altitude code as reported by an onboard air traffic control (ATC) transponder. The concern here is with reported altitude; flight technical error and indicated altitude error will not be considered.

Altimetry system performances are presented in statistical terms by identifying standard deviations of the output of system elements and of the total system. The estimated standard deviations are combined using the root-sum-square (RSS) methodology. The predicted accuracies of subelements are combined this way to estimate the accuracies of system elements, which are further combined to derive the accuracy of the total system.

An altimetry system can be divided into three major elements consistent with system functions. The major elements are:

1. The static system
2. The transducer
3. The quantizer (or Mode C encoder)

These major elements then have associated with them error components as shown in Figure K-1.

These error components are common to all altimetry systems but will be discussed only with reference to the two classes identified above. Technically both classes are controlled by the Federal Aviation Regulations and associated standards (References 14-17). However, investigation of the standards and regulations for altimetry systems, plus observations of levels of equipage, indicate that the altimetry performances of the two are generally governed by different standards. Specifically, the ADC corrected altimetry systems often provide altimetry data in conformance with the performance standards specified in the ARINC Characteristics for Air Data Systems (Reference 18-22). Baseline altimetry system equipment, on the other hand, is controlled primarily by the Federal Aviation Regulations (FARs) and is found primarily among GA aircraft.

## K.1 Performance of a Selected Class of Air Data Computer (ADC) Corrected Altimetry Systems

The altimetry accuracies estimated in this section pertain primarily to ADC corrected altimetry systems in air carrier aircraft. Studies of air carrier aircraft reveal that many are equipped with at least one air data computer (ADC). Many ADCs provide altimetry error correction. (Note that not all aircraft equipped with an ADC provide the error correction function, some ADCs provide only an autopilot capability. Also, it is important to realize that some aircraft without ADC corrected altimetry provide altimetry accuracies equivalent to those in which ADC corrections of static source error are provided. Additionally, some aircraft are equipped with a static defect correction module that compensates for static

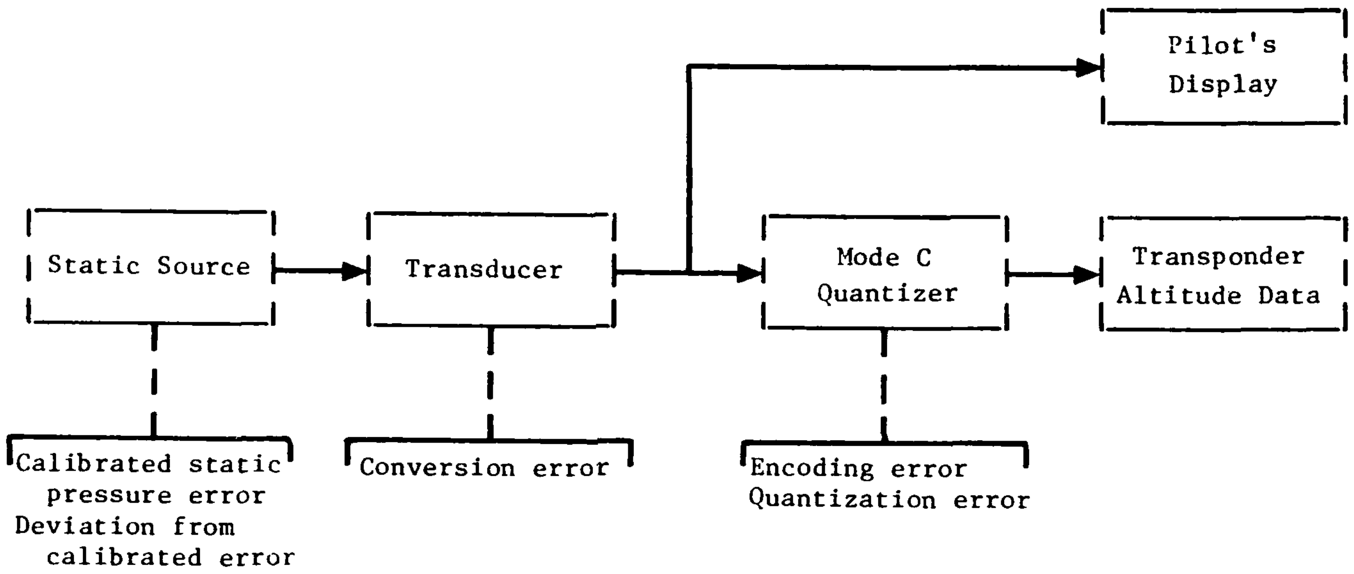



**FIGURE K-1**
**ALTIMETRY SYSTEM ELEMENTS AND ERROR COMPONENTS**

system errors in the same manner as an ADC, and that provides a comparable level of performance.) The ADCs generally conform to or can meet various ARINC Air Data Systems (ADS) characteristics, providing different degrees of accuracy and system performance. Some aircraft, although not the majority of them, are still equipped with the Kollsman Integrated Flight Instrumentation System (KIFIS). From available information on the KIFIS (References 23 and 24), it appears that they exhibit characteristics not unlike those standardized by the ARINC 545 ADS Characteristic.

The estimates in this report of ADC corrected altimetry system component errors are based on an altimetry system as characterized by ARINC Characteristic 545. This is the first of the ARINC characteristics for ADSs and, from an informal survey of the industry, is the one to which most ADC-equipped aircraft conform. Also, it is the least rigorous in system accuracy requirements, the later ADS characteristics requiring better performance. Several error components not covered by this characteristic will be drawn from other sources.

### K.1.1 Static Source Error

Static source error is comprised of the following component sources of errors:

1. Angle-of-attack effects
2. Mach effects
3. Calibration
4. Aircraft-to-aircraft static source variability

Error correction as provided by an ADC can be expected to reduce the overall error of the aircraft's static source, particularly in cases where the uncompensated error is as large as 100 feet or greater. Among errors that are not compensated are those associated with the calibration of the static source both at certification and thereafter, and the aircraft-to-aircraft variability in static source performance due to non-uniformities in aircraft structure, installation, and airframe aging. Errors contributed by angle of attack are also usually uncompensated, although such compensation can be provided and is provided on later model aircraft.

Mach effects are compensated by the ADC through the use of a static source error correction curve. This curve provides an appropriate error correction based on Mach. Based on aircraft flight profiles and performance envelopes, it represents a "fair" or "best fit" error approximation drawn from tests conducted at the time of aircraft certification.

The static system "deviation" error includes the expected offset errors from the calibrated static source error attributable to calibration errors, production tolerances, and in-service degradation of the static system. The magnitude of static system deviation error has been estimated here by taking data from tests of air carrier aircraft (Reference 25) and comparing it to what is suggested by past studies and measurements regarding altimetry systems (Reference 26). Available data indicates that the expected bandwidth of the deviation from the approved error correction curve is approximately 0.9 percent of the impact pressure. The error distribution was assumed to be uniform between the given bandwidth limits. This assumption of uniformity provided the basis for approximations of error bandwidths at selected altitudes and Mach using derived impact pressures. These bandwidth limits were then divided by the square root of 12 to give the standard deviation of the static source deviation error as shown in Table K-1. (Note that at the altitudes of 35,000 and 40,000 ft, the Mach figures tend to exceed what may be considered a representative cruise Mach. This was intentional and should merely serve to make the error estimates more conservative.)

As mentioned, the ADC provides a static source error correction consistent with the correction curve derived from flight test measurements of a particular aircraft type. This curve is generally represented by discrete data points that can be "programmed" into the ADC. Since accurate error correction is largely dependent on the "slope" of the error correction curve, that is the gradient of the error correction versus Mach curve, the number of discrete data points used in the correction is usually increased where the curve's slope is the steepest. The ADC outputs a correction based on the discrete data points providing an interpolation of the intermediate values. From information obtained through informal conversations with ADC manufacturers, it appears that a reasonable level of expected performance of an ADC is error correction to within ± 20 ft of the approved correction curve at any given point. This error is taken as the extreme values of a uniform distribution, which implies that the standard deviation of the static source error correction residual

TABLE K-1
ESTIMATED STANDARD DEVIATION IN STATIC SOURCE ERROR AS A FUNCTION OF MACH AMONG SELECTED ADC CORRECTED ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FT) | MACH | STATIC SOURCE DEVIATION (FT) |
|---|---|---|
| SL | .51 | 28 |
| 5 K | .56 | 32 |
| 10 K | .60 | 37 |
| 15 K | .64 | 42 |
| 20 K | .69 | 47 |
| 25 K | .73 | 52 |
| 30 K | .78 | 56 |
| 35 K | .82 | 62 |
| 40 K | .87 | 70 |

is 12 ft (40 divided by the square root of 12) as shown in Table K-2 under the S.S.E.C. column.

The final variable to be included in this assessment is angle of attack. This variable influences the total static source error but, as indicated from informal conversations with airframe manufacturers, is not compensated in most ADC equipped aircraft. Here, however, it will be addressed since it appears to be a significant component of the static source error. Information that has been obtained informally from manufacturers has resulted in the estimates shown in Table K-2.

For a properly designed system, pneumatic lags should result in no more than a 10 ft error in the pressure altitude input to the transducer, even at vertical rates up to 5000 feet per minute. (See Reference 28.) Given this small error and the likelihood that the aircraft will exhibit virtually no such error for the greatest part of their flights, it is not included in the computation of total system errors.

Table K-2 also gives the total estimate of the standard deviation of ADC compensated static source accuracy. This estimate was derived by taking the root-sum-square of the component errors since they are judged to be independent.

As can be seen, the static source error standard deviation is expected to be of significant magnitude, particularly at high altitudes.

TABLE K-2
ESTIMATED STANDARD DEVIATION IN TOTAL STATIC SYSTEM
PERFORMANCE AMONG SELECTED ADC CORRECTED ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FT) | SS DEV. (TABLE 3-1) | S.S.E.C. | ANGLE OF ATTACK | TOTAL STD. DEV. (FT) |
|---|---|---|---|---|
| SL | 28 | 12 | 5 | 31 |
| 5 K | 32 | 12 | 10 | 36 |
| 10 K | 37 | 12 | 13 | 41 |
| 15 K | 42 | 12 | 16 | 46 |
| 20 K | 47 | 12 | 18 | 52 |
| 25 K | 52 | 12 | 20 | 57 |
| 30 K | 56 | 12 | 22 | 61 |
| 35 K | 62 | 12 | 24 | 68 |
| 40 K | 70 | 12 | 25 | 75 |

### K.1.2 Transducer Error

The next area of interest is transducer error. Referring again to Figure K-1, it can be seen that transducer error is due to the imperfect conversion of pressure into mechanical movement. This conversion error is comprised of a number of components. The ARINC 545 document gives a table of altitude accuracies which are two sigma (95 percent) values. These accuracies have been used here with intermediate values being determined through a linear interpolation. Here, also, the one sigma values are used as shown in Table K-3. The error components accounted for by the ARINC accuracy requirements include friction, hysteresis, threshold sensitivity, repeatability, and test equipment errors.

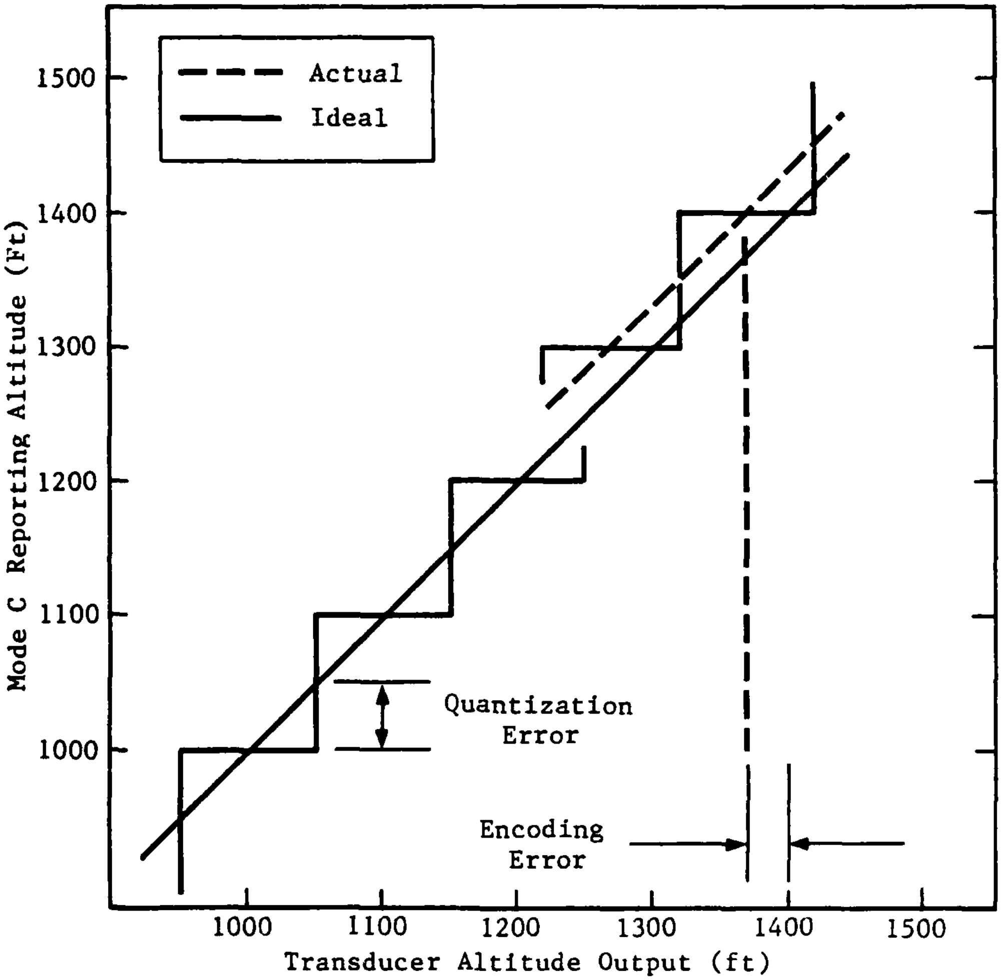
### K.1.3 Quantizer (Mode C) Error

The final errors to be considered are those associated with Mode C altitude reporting. Figure K-2 shows the components of error and their meaning. The *ARINC 545 Characteristic* has no specific requirement for Mode C encoding error. However, later characteristics require a two sigma encoding error limit of 15 ft. This requirement is seen, for instance, in the ARINC 565 ADS standard which essentially is the 545 document with "no-options" for interfacing with peripheral devices. The encoding error standard deviation (one sigma) is thus assumed to be 8 ft.

In addition to the encoder error, there is the 100 foot quantization used in Mode C which causes the report to be in error by 50 ft at the encoder transition points even where

TABLE K-3
ESTIMATED STANDARD DEVIATION IN TRANSDUCER PERFORMANCE
AMONG SELECTED ADC CORRECTED ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FT) | TRANSDUCER ERROR (FT) |
|---|---|
| SL | 12 |
| 5 K | 12 |
| 10 K | 12 |
| 15 K | 19 |
| 20 K | 25 |
| 25 K | 31 |
| 30 K | 38 |
| 35 K | 44 |
| 40 K | 50 |




Note: The quantization error is fixed at 50 ft by the Mode C code. Encoding error is introduced when the center of encoding interval does not fall at an even 100 ft of transducer altitude output.

**FIGURE K-2**
**MODE C ENCODING AND QUANTIZATION ERRORS**

there is no encoding error. Quantization error is uniformly distributed and results in a standard deviation of 29 ft (100 divided by the square root of 12).

The encoding and quantizing errors are independent. When they are root-sum-squared to determine the total error standard deviation, the result is 30 ft, and is shown as such in Table K-4.

K.1.4 ADC Corrected Altimetry System Total Error

Table K-4 shows the computed errors for static source, transducer, Mode C quantizer, and, in the two right-most columns, the estimated standard deviation of total altimetry system error computed using the root-sum-square method. This error budget is intended to represent a general estimate of the standard deviation in altimetry system accuracy for air carrier aircraft of the U.S. fleet with ADC-corrected altimetry.

K.1.5 Altimetry Error Estimates for Specific Airframes

RTCA SC-147 asked several aircraft manufacturers to assess the feasibility of the air carrier quality error budget. Two manufacturers supplied "worst case" altimetry system error budgets for several airframes and kinds of altimetry equipment. These are specified at 5000 ft intervals for Douglas aircraft, and above and below 15,000 ft for Lockheed aircraft. Table K-5 presents this data. The first two columns show altitude and the three standard deviation (99.7 percent probability) budget as taken from the previous section. It is seen that the table entries are below the budget values.

TABLE K-4
ESTIMATED STANDARD DEVIATON IN TOTAL ALTIMETRY SYSTEM
PERFORMANCE AMONG SELECTED ADC CORRECTED ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FT) | STATIC SOURCE | TRANSDUCER | QUAN. (MODE C) | TOTAL STD. DEV. (FT. ) W/O Mode C | W/Mode C |
|---|---|---|---|---|---|
| SL | 31 | 12 | 30 | 33 | 45 |
| 5 K | 36 | 12 | 30 | 38 | 48 |
| 10 K | 41 | 12 | 30 | 43 | 52 |
| 15 K | 46 | 19 | 30 | 50 | 58 |
| 20 K | 52 | 25 | 30 | 58 | 65 |
| 25 K | 57 | 31 | 30 | 65 | 71 |
| 30 K | 61 | 38 | 30 | 72 | 78 |
| 35 K | 68 | 44 | 30 | 81 | 86 |
| 40 K | 75 | 50 | 30 | 90 | 95 |

TABLE K-5
WORST-CASE ALTIMETRY ERROR FOR CERTAIN AIR CARRIER JETS

| ALT | 3 SIGMA FROM TABLE 4-13 | DC-8-60/70 (1) | DC-8-60/70 (4) | DC-9-30 (2) | DC-9-10/ (3) | DC-9-10/30/40/50 (4) | DC-9-30/40/50 (5) | DC-9-80 (6) | DC-10 ALL (6) |
|---|---|---|---|---|---|---|---|---|---|
| SL | 135 | 76 | 67 | 66 | 55 | 55 | 55 | 66 | 121 |
| 5 K | 144 | 85 | 68 | 77 | 56 | 56 | 56 | 68 | 123 |
| 10 K | 156 | 70 | 51 | 113 | 63 | 63 | 63 | 81 | 71 |
| 15 K | 174 | 92 | 72 | 147 | 73 | 73 | 73 | 89 | 109 |
| 20 K | 195 | 92 | 75 | 164 | 76 | 76 | 76 | 92 | 112 |
| 25 K | 213 | 85 | 71 | 163 | 57 | 57 | 57 | 76 | 100 |
| 30 K | 234 | 136 | 117 | 235 | 116 | 148 | 148 | 70 | 83 |
| 35 K | 258 | 136 | 121 | 258 | 121 | 153 | 153 | 76 | 88 |
| 40 K | 285 | 136 | 126 | - | - | - | - | - | 94 |

NOTES:

1. Numbers in parentheses under aircraft types reflect altimetry equipment configurations as follows:

(1) KIFIS altimeter and encoder
(2) Encoding pneumatic altimeter
(3) Pneumatic altimeter/air data computer (ADC) encoder
(4) Servo-pneumatic altimeter/ADC encoder
(5) Electric indicator/ADC encoder
(6) Electric indicator/digital ADC (DADC) encoder

2. The estimates given by Lockheed for Lockheed aircraft were not specified in enough detail to accurately reflect their performance at the altitudes shown above. The values Lockheed gave were applicable to: a) sea level to 15,000 feet and below approximately Mach .6 and b) above 15,000 feet at Mach .82, cruise. Note that both Lockheed aircraft provide static source error correction (SSEC) above 15,000 feet based only on Mach. The worst case estimates given were:
   a) For the L1011-385-1, at or below 15,000 feet the worst case error is 145 feet. Above 15,000 feet the worst case case error is 220 feet.
   b) For the L1011-385-3, at or below 15,000 feet, the worst case error is 131 feet. Above 15,000 feet the worst case error is 200 feet.

## K.2 Performance of Baseline Altimetry Systems

The baseline altimetry system performance usually pertains to systems that are likely to be found aboard GA aircraft. These aircraft generally have mechanical transducers with no internal or external correction devices. Often, the mechanisms for encoding altitude for Mode C reports is contained in a totally separate transducer called a "blind" encoder. The only link between the altimeter and the blind encoder is the common static system. Other aircraft may be found to be equipped with an encoding altimeter. Some high performance aircraft, such as jets do have the added feature of static defect correction (SDC) which can greatly improve altimeter and Mode C accuracy. (The SDC provides an ADC type of error correction function.) An SDC module is expensive (on the order of $7,500 or more) and its application thus far is generally limited to high performance and high cost aircraft. The following estimates of error magnitudes are based on systems not employing SDC modules.

In addition to inferring altimetry performance from the pertinent regulations, a survey of aircraft manuals, and a survey of manufacturers as described above, a set of measurements was made in 1975. Here, the actual altitudes of 45 GA aircraft were repeatedly measured at 4500 and 8500 foot altitudes and compared to the reported values, thus measuring total error (Reference 30). To generate meaningful statistics, these error measurements were converted by an approximate method to the single altitude of 4500 ft (Reference 31).

### K.2.1 Static Source Error

For the low performance aircraft that generally incorporate a baseline altimetry system, the static source error components considered are the following: calibrated static source error, static source deviation, and angle of attack errors.

To estimate a representative calibrated static source error for GA aircraft, the readily available error correction charts were examined and records made of the observed worst case errors. Then, to be conservative, it was assumed that these errors characterized the limiting values of a uniform error distribution. From these uniform distributions, the standard deviation was found through dividing the total error bandwidth by the square root of 12. The second column in Table K-6 shows the estimated standard deviations of static error at various altitudes. It is noted that ADC or SDC corrected altimetry systems should perform considerably better.

Table K-6 also shows the estimates of the expected deviations from the calibrated static source errors and includes calibration errors, production tolerances, and overall aircraft-to-aircraft variability in static source performance. There was little information available on aircraft-to-aircraft variability in static system performance either within model lines or on the basis of aircraft age. Therefore, the figures shown were drawn from a staightforward multiplication, by 1.25, of the air carrier standard deviations.

Angle of attack errors are also shown in Table K-6. Angle of attack does contribute to the error, although the contribution is usually not of great significance, given the low airspeeds and weight limitations of GA aircraft. Error magnitudes associated with angle of attack effects are included to be conservative and are based primarily on information offered by manufacturers. Some substantiating evidence for the given figures can be extracted from pilot's manuals for high performance GA aircraft where error deviation with gross weight is illustrated by the correction charts. On several high performance GA aircraft,

TABLE K-6
ESTIMATED STANDARD DEVIATION IN TOTAL STATIC SYSTEM
PERFORMANCE AMONG BASELINE ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FT) | STATIC ERROR | DEVIATION ERROR | ANGLE OF ATTACK | TOTAL STD. DEV. (FT) |
|---|---|---|---|---|
| SL | 69 | 35 | 10 | 78 |
| 5 K | 84 | 40 | 20 | 95 |
| 10 K | 95 | 46 | 27 | 109 |
| 15 K | 109 | 52 | 32 | 125 |
| 20 K | 121 | 59 | 37 | 140 |
| 25 K | 135 | 65 | 40 | 155 |
| 30 K | 147 | 70 | 43 | 168 |
| 35 K | 161 | 78 | 47 | 185 |
| 40 K | 173 | 88 | 50 | 200 |

several such charts are provided each showing the required correction-versus-airspeed for differing gross weights (angles of attack). The given deviation with gross weight can be used to determine angle of attack effects.

The last column of Table K-6 shows the total static system standard deviation which was derived using the RSS method.

### K.2.2 Transducer Error

As shown in Figure K-1, the transducer error is due to the imperfect conversion of pressure to mechanical movement. The estimations of transducer error for a fully mechanical altimeter are derived in part from the FAR, Part 43, Appendix E. The accuracies shown here are based on the scale and hysteresis error limits shown in the FAR. These error limits are assumed in each case to represent the three sigma error limits. The standard deviation for these two combined errors was then calculated as the RSS of the specified error limits divided by three.

Another error source considered was transducer calibration accuracy. From available information (Reference 26), it appears that these errors shall fall within approximately 0.005 in Hg at sea level (5 ft) and within 0.003 in. Hg at 70,000 ft (50 ft). These values were assumed to represent the error standard deviations with intermediate values being derived through a linear interpolation.

The error standard deviations shown in Table K-7 were derived by the RSS combination of the standard deviations of both the FAR requirements and the calibration accuracies at each given altitude.

TABLE K-7
ESTIMATED STANDARD DEVIATION IN TRANSDUCER PERFORMANCE
AMONG BASELINE ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FEET) | STANDARD DEVIATION (FEET) |
|---|---|
| SL | 26 |
| 5 K | 29 |
| 10 K | 38 |
| 15 K | 45 |
| 20 K | 52 |
| 25 K | 61 |
| 30 K | 69 |
| 35 K | 77 |
| 40 K | 86 |

K.2.3 Quantizer (Mode C) Error

All aircraft must, as a minimum, meet the requirements of FAR Part 91.36. This regulation requires that the quantized altitude, as used in the Mode C altitude report, correspond to the indicated altitude to within ± 125 ft on a 95 percent (two sigma) probability basis at the time of equipment installation. The indicated altitude, in this case, is as corrected to 29.92 in. Hg. Using this requirement as an indicator of actual performance gives a standard deviation of 63 ft (one sigma) at all altitudes.

Recently, a new FAR Mode C test has been established that requires a bi-annual check of Mode C correspondence to indicated altitude for aircraft flown under instrument flight rules (IFR). The operational limits to correspondence error are ± 300 ft. If ATC sees an error of this magnitude, they may request that the Mode C report be turned off.

K.2.4 Baseline Altimetry System Total Error

Table K-8 shows the computed standard deviations for static source, transducer, and quantizer errors. In addition, the two right hand columns show the standard deviations for total system error using the RSS method. This error budget is intended to represent the nominal standard deviation in baseline altimetry system accuracy, primarily among GA aircraft of the U.S. fleet.

As noted earlier, a limited set of measured data is available for GA altimeters (References 30 and 31). This information (converted to 4500 ft altitude) showed a standard deviation in indicated altitude of 68 ft, considerably less than the 99 ft shown in Table K-8 at 5000 ft altitude. This implies less

TABLE K-8
ESTIMATED STANDARD DEVIATON IN TOTAL ALTIMETRY SYSTEM
PERFORMANCE AMONG BASELINE ALTIMETRY SYSTEMS

| ALTITUDE (MSL) (FEET) | STATIC SOURCE | TRANSDUCER | QUAN.- (MODE C) | TOTAL STD. W/O Mode C | DEV. (FT.) W/Mode C |
|---|---|---|---|---|---|
| SL | 78 | 26 | 63 | 82 | 104 |
| 5 K | 95 | 29 | 63 | 99 | 118 |
| 10 K | 109 | 38 | 63 | 115 | 132 |
| 15 K | 125 | 45 | 63 | 132 | 147 |
| 20 K | 140 | 52 | 63 | 149 | 162 |
| 25 K | 155 | 61 | 63 | 166 | 178 |
| 30 K | 168 | 69 | 63 | 182 | 192 |
| 35 K | 165 | 77 | 63 | 200 | 210 |
| 40 K | 200 | 86 | 63 | 218 | 227 |

static error than is predicted, at least for that sample. On the other hand, the measurements also show a standard deviation in reported altitude of 111 ft (at 4500 ft altitude). This is close to the 118 ft shown in Table K-8 at 5000 ft altitude. The implication is that while the static error is less than predicted, the quantization (encoding) error is greater, ending up with nearly the same results in reported altitude.

## APPENDIX L

## VISUAL ACQUISITION OF ATC ADVISORIES

This appendix discusses the differences between the visual acquisition probabilities calculated in Section 6.5 and visual acquisition experience in the ATC system today. It explains why it is misleading to compare current experience with ATC traffic advisories to the results found in Section 6.5. It also demonstrates that the model gives results consistent with current experience if it is properly applied.

In Section 6.5, the visual acquisition probabilities are computed for a two-man crew searching with the aid of a TCAS traffic advisory. The probability of acquisition by 15 seconds to collision is computed (assuming a zero horizontal miss distance). The acquisition probability is greater than the average value for visual acquisition today for the following reasons:

1. The bearing provided by the TCAS TA is two or three times more accurate than the bearing provided by ATC.

2. ATC often provides advisories for traffic which never approaches closer than 2 or 3 miles. This long-range traffic is harder to acquire than traffic which approaches to within 15 seconds of collision.

3. ATC often provides advisories at ranges of 4 to 5 miles. For small aircraft, this is too soon for productive visual search. Even if the aircraft later comes close enough to be more easily acquired, the bearing has often changed or the search effort of the crew has diminished.

In order to compare the model predictions to current experience, the model should be applied under assumptions which more closely reflect the manner in which ATC traffic advisories are used. As an example, let us make the following assumptions:

1. The model parameter $\beta$ which describes visual search performance with the aid of an ATC traffic advisory will be 70,000/sec (single pilot). This is half the value for a TCAS traffic advisory and reflects the fact the decreased accuracy of the ATC advisory requires the crew to search an angular area which is two or three times greater than with TCAS. It will be assumed that two crew members search so that the effective $\beta$ value is 140,000 for time periods in which both crew members are searching.

2. The ATC traffic advisory is given at 4 nmi before closest approach.

3. The crew devotes half of the 30 second period following the receipt of the advisory to visual search. The acquisition probability is computed at the end of this 30 second period. This assumption is intended to reflect the fact that as the time passes the search effort of the crew diminishes and the bearing of the intruder tends to change, making visual acquisition less likely.

4. The intruder has a visible area of 70 square feet (assumed constant for purposes of calculation). Actual visual areas for small aircraft range from 20 to 120 square feet.

For unaccelerated flight the range to the target is given by the expression

$$r = (m^2 + V^2t^2)^{1/2}$$

where m is the horizontal miss distance, V is the relative speed of the intruder, and t is the time to closest approach. The probability of acquisition is then given by the expression

$$P\ [\text{acquisition}] = 1. - \exp\left[-\frac{\beta A}{Vm}\left(\arctan\frac{Vt_1}{m} - \arctan\frac{Vt_2}{m}\right)\right]$$

where A is the target visible area, $t_1$ is the time at which search begins, and $t_2$ is the time at which search ends (all times being measured relative to the time of closest approach.) If the miss distance approaches zero, this expression reduces to the familiar expression used in the safety study:

$$P\ [\text{acquisition}] = 1. - \exp\left[-\frac{-\beta A}{\dot{r}^2}\ \frac{t_1 - t_2}{t_1 t_2}\right]$$

The visual acquisition probabilities which result are provided in Table L-1 for a combination of relative speeds and miss distances.

TABLE L-1
PREDICTED PROBABILITY OF VISUAL ACQUISITION WITH
ATC TRAFFIC ADVISORIES (EXAMPLE)

| RELATIVE SPEED | HORIZONTAL MISS DISTANCE | | | |
|---|---|---|---|---|
| | 0.0 nmi | 1.0 nmi | 2.0 nmi | 3.0 nmi |
| 120 Knots | 0.28 | 0.26 | 0.22 | 0.17 |
| 240 Knots | 0.39 | 0.35 | 0.27 | 0.15 |
| 360 Knots | 0.64 | 0.51 | 0.23 | 0.16 |

The average probability of acquisition for this example is around 30 percent, much lower than the model predictions which are appropriate for use in NMAC geometries. The acquisition probability would be greater if the examples were elaborated to include acquistion which occurs more than 30 seconds after the traffic call. The acquisition probability would go down if altitude-unknown traffic advisories were included or if cases of greatly restricted meterological visbility were added.

The example demonstrates that the visual acquisition model employed in this study is not necessarily inconsistent with stated experience with ATC traffic advisories.

## APPENDIX M

## UNITED AIRLINES RISK DATA

From records kept by United Airlines (UAL), and made available for this study, it is possible to estimate the average risk of encountering a critical near midair collision.

Over the period of January 1980 to July 1983 the UAL fleet logged 2,922,500 flight hours. They also recorded any near midair collisions that their pilots reported, noting the altitude at which they occurred and often the estimated vertical or horizontal separation at closest approach. From this data, all reports occurring at less than 500 ft AGL were removed, to correspond to a similar provision that is built into TCAS. For those incidents where relative altitude was estimated, approximately 25 percent were noted to come within 100 ft vertically; and there were a total of 60 incidents. For those incidents where horizontal miss distance was estimated, 22 out of 23 cases were reported within 500 ft. From this information, the risk of encountering a critical near midair collision is estimated to be:

$$(60 \times .25)\ (22/23)/2,922,500 = 4.9 \times 10^{-6} \text{ per hour.}$$

# APPENDIX N

## ACRONYMS AND ABBREVIATIONS

A/C - Air Carrier

ADC - Air Data Computer

ADS - Air Data Systems

AGL - Above Ground Level

ALIM - Altitude threshold for corrective resolution advisories

ARINC - Aeronautical Radio, Inc.

ATARS (IPC) - Automatic Traffic Advisory and Resolution Service (Intermittent Positive Control)

ATC - Air Traffic Control

ATCRBS - Air Traffic Control Radar Beacon System

BCAS - Beacon Collision Avoidance System

CAS - Collision Avoidance System

CPA - Closest Point of Approach

CRT - Cathode Ray Tube

DoD - Department of Defense

FAA - Federal Aviation Administration

FAR - Federal Aviation Regulations

GA - General Aviation

HMD - Horizontal Miss Distance

IFR - Instrument Flight Rules

ILS - Instrument Landing System

IMC - Instrument Meteorological Conditions

IPC - See ATARS

KIFIS - Kollsman Integrated Flight Instrumentation System

LCK bit - Coordination Lock subfield used in TCAS-to-TCAS coordination

MOPS - Minimum Operational Performance Standard

MSL - Mean Sea Level

NASA - National Aeronautics and Space Administration

NMAC - Near Midair Collision

NMI - Nautical Miles

RA - Resolution Advisory

RSS - Root-Sum-Squares

RTCA - Radio Technical Commission for Aeronautics

SDC - Static Defect Correction

SS - Static Source

SSEC - Static Source Error Correction

SSR - Secondary Surveillance Radar

TA - Traffic Advisory

TCAS - Traffic Alert and Collision Avoidance System

TCAS I - Version of TCAS giving minimal warnings

TCAS II - Version of TCAS giving resolution advisories

TEU - TCAS Experimental Unit

VFR - Visual Flight Rules

VMC - Visual Meteorological Conditions

VMD - Vertical Miss Distance

ZTHR - Altitude threshold for preventive resolution advisories

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